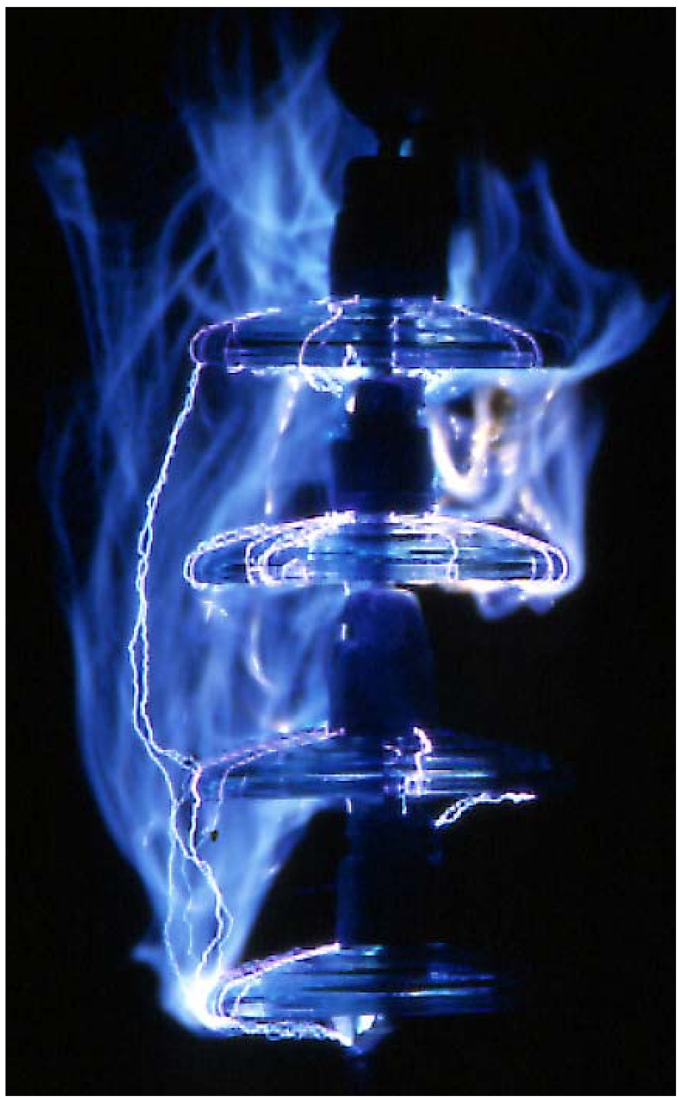
High Voltage Engineering

Practice and Theory



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Contents

1 INTRODUCTION TO HIGH VOLTAGE POWER SYSTEMS 1

1.1 Historical Overview 1
1.2 Power Network 3
1.2.1 Energy sources and energy conversion 5
1.2.2 Generators 7
1.2.3 Substations 8
1.2.4 Power lines and cables 9
1.3 Basic Equipment 11
1.3.1 Power lines: towers, conductors, metal ware and insulators 11
1.3.2 Underground power cables 12
1.3.3 Bushings 13
1.3.4 Power transformers 15
1.3.5 Instrument transformers: current transformers (CT's) and voltage transformers (VT's) 15
1.3.6 Line traps (LT's) 20
1.3.7 Circuit breakers and fuses 20
1.3.8 Isolators 25
1.3.9 Surge arresters or lightning arresters (LA's) 26
1.4 Conclusion 26
1.5 Review Questions 27

2 FIELDS 28

2.1 What is a field? 28
2.2 Electrostatic Fields 29
2.2.1 Uniform fields 29
2.2.2 Non uniform fields 30
2.2.3 Bundle conductors and grading 35
2.2.4 Mixed dielectrics 37
2.2.5 Capacitive coupling 40
2.3 Magnetic Fields 40
2.3.1 Magnetic induction: inductive coupling 41
2.4 Electrical Conduction Fields 42
2.5 Thermal Fields 43
2.6 Health Effects 43
2.7 Field Analysis Methods 44
2.8 Review Questions 45

3 HIGH VOLTAGE INSULATING MATERIALS 47

3.1 Gases 47
3.1.1 Ionization 48
3.1.2 Electronegative gases, attachment and de-ionization 50
3.1.3 Self-sustained gas discharges: Townsend discharges 51
3.1.4 Self-sustained gas discharged: streamer discharges 52
3.1.5 Flashover of uniform gaps: The effect of pressure and gap length (Paschen's Law) 52
3.1.6 Flashover of non-uniform gaps: the polarity effect 55
3.1.7 Flashover mechanism of long gaps: Leader mechanism 56
3.1.8 Flashover, sparks and arcs 57
3.1.9 Corona discharges 59
3.2 Solid and Liquid Insulating Materials 64
3.2.1 Dielectric constant (ε) 64
3.2.2 Losses in dielectrics (tan δ) 65
3.2.3 Typical solid insulating materials 65
3.2.4 Failure mechanisms of solid insulating materials 67
3.2.5 Liquid insulating materials 69
3.2.6 Failure mechanisms of insulating liquids 70
3.3 The Performance of Combinations of Gases, Solids and Liquids in Insulation Systems 72
3.3.1 Parallel insulating materials 73
3.3.2 Series insulating materials 73
3.4 Insulator Pollution 78
3.4.1 Form Factor Calculation 80
3.5 Summary of Properties of Insulating Materials 81
3.6 Review Questions 82

4 HIGH VOLTAGE TESTING AND MEASUREMENT 86

4.1 Generation of High Voltages 86
4.1.1 Power frequency voltage and current (AC) 86
4.1.2 Direct current (DC) 88
4.1.3 Lightning and switching impulses 90
4.2 Measurement 91
4.2.1 Voltage dividers 92
4.2.2 Peak and RMS voltmeters 94
4.2.3 Sphere gap for voltage measurement 95
4.2.4 Electrostatic voltmeters 95
4.3 Laboratory Testing 95
4.3.1 Interpretation of AC, DC and Impulse test results 96

4.3.2 Non-destructive tests 96
4.4 Review Questions 100

5 OVERVOLTAGES AND INSULATION CO-ORDINATION 102

5.1 Insulation Co-ordination 102
5.1.1 Basic principles 102
5.1.2 Standard insulation levels 103
5.2 Power System Overvoltages 104
5.2.1 Power frequency overvoltages 104
5.2.2 Switching overvoltages 106
5.2.3 Lightning overvoltages 107
5.3 Surge Protection 115
5.4 Coordinated wood pole insulation coordination 117
5.5 Specifications 117
5.6 Review Questions 121

6 HIGH VOLTAGE SAFETY PRINCIPLES 123

6.1 Judiciary Aspects 123
6.1.1 Effect of electrical currents on the human body 124
6.1.2 Electrical clearances 125
6.1.3 Safety signs and working procedures 126
6.2 Capacitive and Inductive Coupling, Floating Objects, Current Loops 127
6.3 Safety Earthing 127
6.3.1 Working earths 127
6.4 Step and Touch Potential, Equipotential Platforms and Voltage Transfer 129
6.5 Safety in the High Voltage Laboratory 130
6.6 Review Questions 131

1 INTRODUCTION TO HIGH VOLTAGE POWER SYSTEMS

Nicola Tesla: The man who made alternating current power networks possible …

1.1 Historical Overview

During power blackouts we realise our dependence on the power system and high voltage in particular. How did it happen that we became so dependant upon electricity – something that is actually invisible?

The natural phenomena were there, just waiting to be tamed by geniuses of the kind of Michael Faraday, the Father of Electricity. In this process each inventor or scientist built on the work of others. As Sir Isaac Newton humbly put it in 1675: "If I can see further, it is by standing on the shoulders of giants."

It all started in ancient Greece. The Greek philosopher Thales of Miletus in 600 B.C. described the phenomenon of static electricity which was already known to the Greeks. They noticed that sparks could be produced by rubbing amber with fur. The Greek word for amber is "elektron" and the Englishman William Gilbert in 1600 coined the Latin word "electricus" from which the word "electricity" later developed.

The Dutchman Pieter van Musschenbroek invented the Leyden jar, the first electrical capacitor, in 1745. Shortly afterwards, William Watson proved, using a Leyden jar, that a discharge of static electricity is actually an electric current. In June 1752 Benjamin Franklin, the American statesman, performed his famous dangerous kite experiment during a thunder storm and showed that lightning is associated with the flow of a large electric current.

The research of two Italians, Luigi Galvani (1737 – 1798) and Alessandro Volta (1745 – 1827) on the interaction between metal electrodes and a chemical electrolyte was the forerunner of the electric battery. It was however not Chemistry that would furnish the main source of electricity, but Physics.

Faraday was born in 1791 near London as the son of a poor blacksmith and received only a few years' formal education. Only 13 years old, he started to work at a bookbinder's shop in London. He started experimenting with electricity and may rightly be regarded as the inventor of the main principles that form the basis of the generation, transmission and

utilization of electricity: the generator, the transformer and the electric motor. His major contribution was Faraday's Law, which states that, when a piece of copper wire moves past a magnetic pole, the electrons in the wire tend to move. The amazing fact is that this principle is still responsible for the generation of the bulk of the electric power being generated today.

In power stations, other forms of energy, such as that in fossil fuel, nuclear fuel, hydraulic head or wind, are first converted into mechanical energy and then into three-phase electrical energy when the magnetic field of the rotor "cuts" the copper phase conductors. The main advantage of electrical power is the ease whereby it can be transmitted over long distances to remote parts of a country.

Thomas Alva Edison (1847 – 1931) patented, after extensive research, the first incandescent light bulb and initiated the construction of the first power station in Pearl Street, New York, including a network that supplied 110 volts DC to 59 clients. During a span of a few years similar power networks were established in the major cities of America, Britain, Europe and even in remote parts of the world, such as Kimberley in South Africa where electric street lights were switched on at the diamond mines on 1 September 1882 – three days before the commissioning of the Pearl Street Power Station in New York.

It was soon realised that a low voltage power lines such as those run by Edison are limited in their length due to voltage drop constraints. Nikola Tesla (1856 – 1943) conceived the concept of alternating current in 1886, together with the concept of using transformers to step up the voltage, causing a proportional reduction in current. The use of higher voltages therefore permitted the construction of longer lines to supply power to remote areas. The use of the higher voltages, however, uncovered the problems associated with high voltage insulation. The effects of the environment such as lightning on the overhead power lines necessitated research and development, leading to the discipline of High Voltage Engineering that forms the basis of this book.

An impolite campaign raged in the late 1880's between Tesla en Edison, the so-called "War of the Currents". Edison, a protagonist of direct current, initiated a business-driven smear campaign against Tesla. Edison stated that alternating current was only useful for the electric chair and he went so far as to attend various executions[1]. Recent research

[1] ..including that of Topsy the Elephant (http:en.wikipedia.org/Topsy_the_Elephant.

indicates that Edison might have had a point as 50 or 60 Hz alternating current apparently more readily induces ventricular fibrillation than direct current. Direct current is however also dangerous and the advantages of alternating current ensured Tesla's victory. Ironically, with the advent of high voltage power electronics devices, direct current has made a comeback. Long high voltage direct current (HVDC) lines are used, even for inter-continental power transmission.

The continued efforts of electrical power engineers during the past century in various countries of the world resulted in the development of sophisticated and surprisingly reliable power grids, considering the size of the networks and the severity of the environmental conditions. In the following sections an overview will be given of the major aspects of such power systems.

1.2 Power Network

In this book the term high voltage is used as a generic term to include all voltages higher than 1000 volts, although the emphasis is on the typical voltage levels used power systems. High voltages, however, feature in many applications that are not related to the power system. Typical examples are automotive ignition systems, cathode ray tubes as found in oscilloscopes and television sets.

A schematic representation of a typical power system is shown in Fig. 1.1.

An important relationship in connection with power transmission is the following:

$$S = \sqrt{3}\,V\,I \tag{1.1}$$

with S, the apparent power in kVA, V the line-to-line voltage in kV and I the line current in A.

This equation clearly shows that, in order to transmit a fixed amount of kVA over a transmission line, a higher voltage is preferable as it results in lower currents. The lower currents are desirable as the losses and voltage drops due to the conductor resistance are lower. This permits the use of thinner conductors.

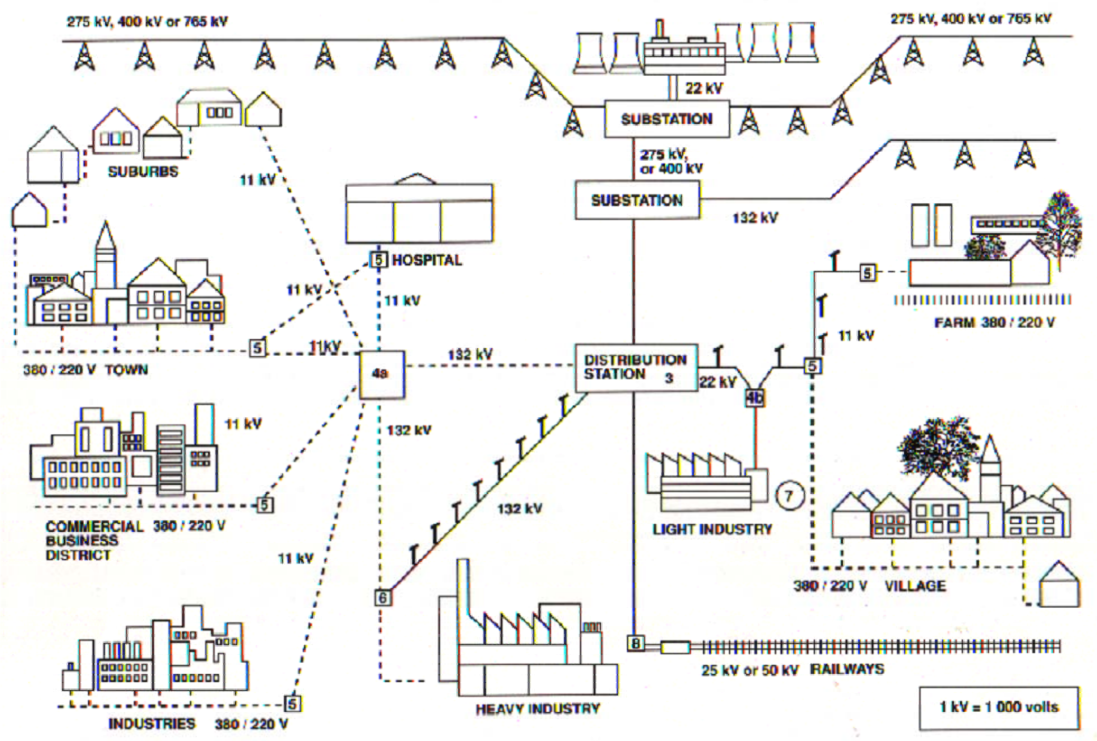


Fig. 1.1: Schematic representation of a power network

The use of higher voltages introduces a number of new aspects that have to be taken into account in order to prevent current leakage or flashover due to inadequate insulation. In general all metals are conductors of electricity due to their higher conductivities, with copper and aluminium being the cost-effective choices. Non-metals are generally non-conductors of electricity, i.e. insulating materials. These include gases in their non-ionized state – air at atmospheric pressure being the most generally applied substance of this type. Pure, deionised water is also an insulating material, but minute quantities of dissolved inorganic salts turn it into a conductor, despite the fact that the salt crystals are insulators when dehydrated. Organic matter, such as wood, is also a good insulator when dry, but becomes conducting when moist. The properties of a number of substances are given in Table 1.1.

From this table air at atmospheric pressure is an obvious choice as an insulating material. This resulted in the widespread use of high voltage overhead lines and outdoor substations. It is however still necessary to support the high voltage conductors mechanically. For this purpose porcelain and glass have given good service as support or suspension insulators. These insulators then appear parallel to the air insulation that surrounds the bare conductor. The interface between the porcelain or glass and air turns out to be a vulnerable region.

Table 1.1: Properties of Conductors and Insulating Materials

	Material	Conductivity (σ), S/m	Permittivity (ε_r)
Conductors	Silver	$6.17 \cdot 10^7$	-
	Copper	$5.8 \cdot 10^7$	-
	Aluminium	$3.82 \cdot 10^7$	-
	Iron	$1.03 \cdot 10^7$	-
	Carbon (graphite)	$1.0 \cdot 10^5$	-
	Water (sea)	4	-
	Water (fresh)	10^{-3}	-
Insulators	Water(distilled)	$2 \cdot 10^{-4}$	80
	Porcelain	10^{-10}	6
	Glass	10^{-10}	5
	Air	-	1.0006
	SF_6	-	1

In metal clad gas insulated systems (GIS), sulphur hexafluoride gas (SF6) is used as the main insulating medium. In addition, solid materials such as porcelain, glass and polymers are also used to support the high voltage conductors. Transformers and other equipment use mineral oil, either on its own or in combination with linen or paper.

In a properly designed system the above mentioned insulation systems should be able to perform reliably under normal voltage conditions as well as under abnormal overvoltage conditions. The main factor that may cause failure of insulation is overstressing, i.e. applying an electric field to the material that exceeds its capabilities and induces failure. Typically, air at atmospheric pressure is a good insulator and a gap consisting of electrodes without sharp protrusions can easily withstand 20 kV/cm. However, at 30 kV/cm the air in the gap becomes ionized and breaks down, leading to a flashover, accompanied by a high short circuit current. Lightning develops similarly when the build-up of electric charge in the cloud causes field conditions, leading eventually to a massive discharge in the form of a high current to ground.

1.2.1 Energy sources and energy conversion

Apart from the direct conversion of solar energy to electricity due to the photo-voltaic effect, all the electricity in the world is generated, using Faraday's Law. Water, steam or wind energy causes rotation of the turbine and generator rotor.

When the magnetic poles on the rotor move past the stator, electricity is induced in the stator windings, producing three phase power as shown in Fig. 1.2.

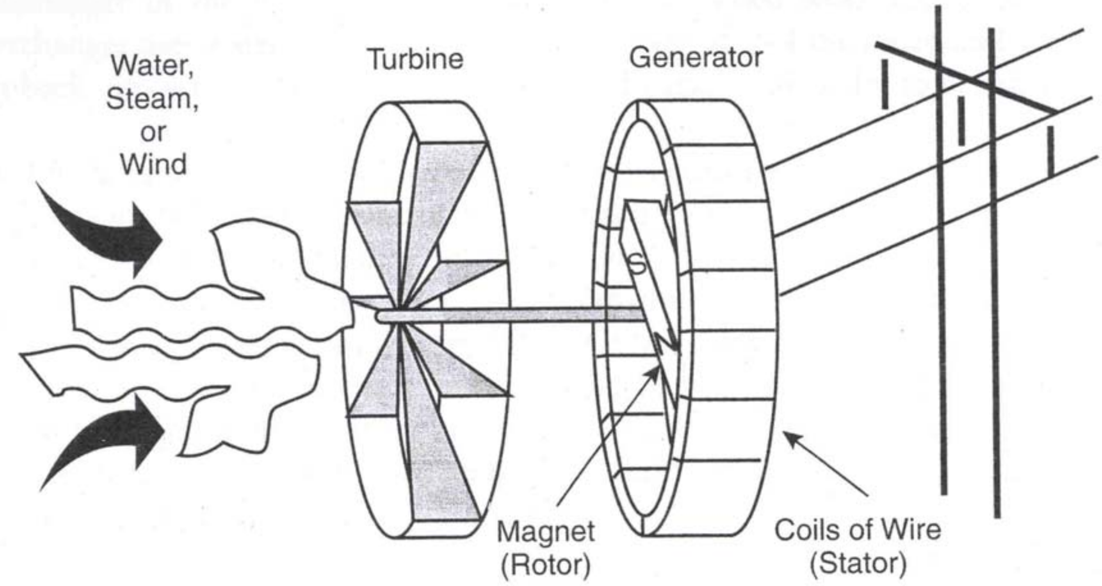


Fig. 1.2: Principle of the generation of electricity, using Faraday's Law.

The principles of hydro and fossil fuel power stations are shown in Fig. 1.3, while those of conventional and pebble bed modular reactors (PBMR) are shown in Fig. 1.4.

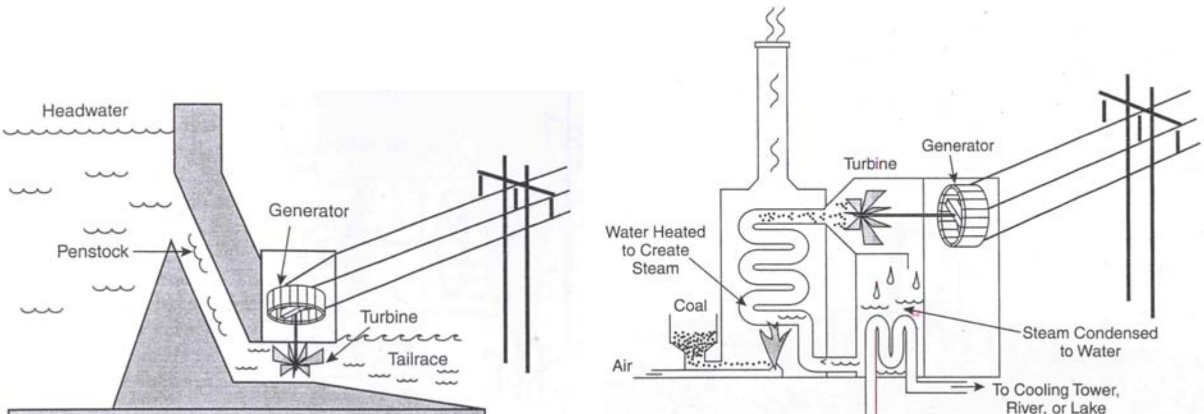


Fig. 1.3: Schematic diagrams, showing the operation of a hydro-electric power station (left) and a coal-fired power station (right)

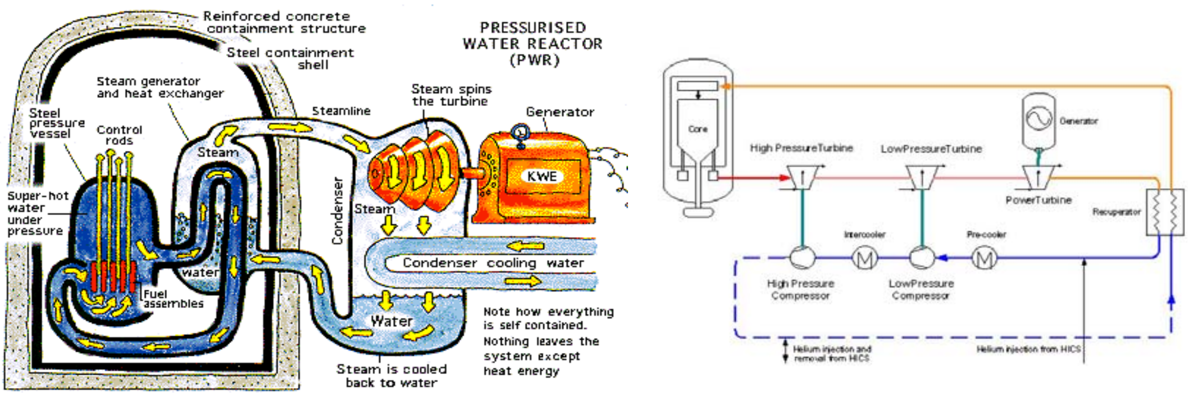


Fig. 1.4: Schematic diagrams, showing the operation of a conventional pressurised water reactor (PWR) power station (left) and a PBMR (right)

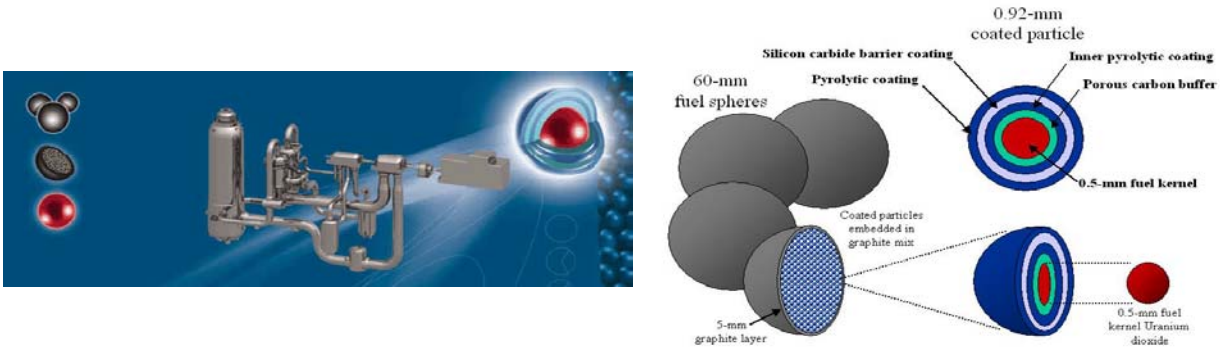
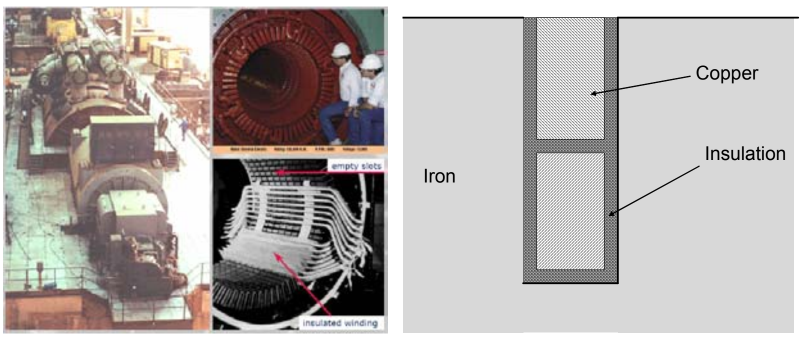


Fig. 1.5: Layout of the PBMR with fuel pebbles shown.

1.2.2 Generators

The rating of a typical large generator is between 500 and 900 MVA and the generator voltage is typically 24 kV. This results in a large full load current of the order of 10 to 20 kA. The losses associated with these high currents necessitate water-cooling of the stator winding and the use of air-cooled bus ducts for the connections between the generator and the generator transformer.



(a) (b)

Figure 1.6: (a) Generator, stator windings and (b) detail of the windng insulation in the stator slot

The insulation of the stator bars relative to the stator slots poses a particularly difficult insulation problem in the light of the limited

space, high voltage and temperature. Mica, bonded with epoxy resin is usually applied as insulation material. Fig. 1.6 gives detail of stator winding insulation.

1.2.3 Substations

The substations are the nodes in the power system where several lines and transformers are connected together as is shown in Fig. 1.1. Transmission substations serve as the interconnection nodes on the main transmission system. At these stations the voltage is raised to the levels of the transmission system and stepped down again to lower distribution levels when appropriate. Typically, distribution stations operate at voltages of 132 kV and below to distribute the power to the points of consumption. A typical distribution substation is shown in Fig. 1.7.

Fig. 1.8 shows sections of a conventional outdoor and of an indoor gas-insulated substation (GIS). In GIS the use of SF_6, a gas with exceptional insulating properties, facilitates the design of very compact substations. In GIS a co-axial tubular system is used and all the components, such as circuit breakers, isolators and circuit breakers form an integral part of the substation.

The incoming and outgoing circuits can be switched to either of the two busbars by means of the busbar selection isolators. Isolators are also provided on both sides of equipment such as transformers and circuit breakers to allow disconnection during maintenance of the equipment. Isolators are not designed to interrupt full load or fault currents and should only be operated under no-load conditions.

Some of the circuits are associated with transformers for stepping the voltage down or up, as the case may be. The most important items of equipment are the circuit breakers, which differ from the isolators in that they can interrupt full load and fault currents.

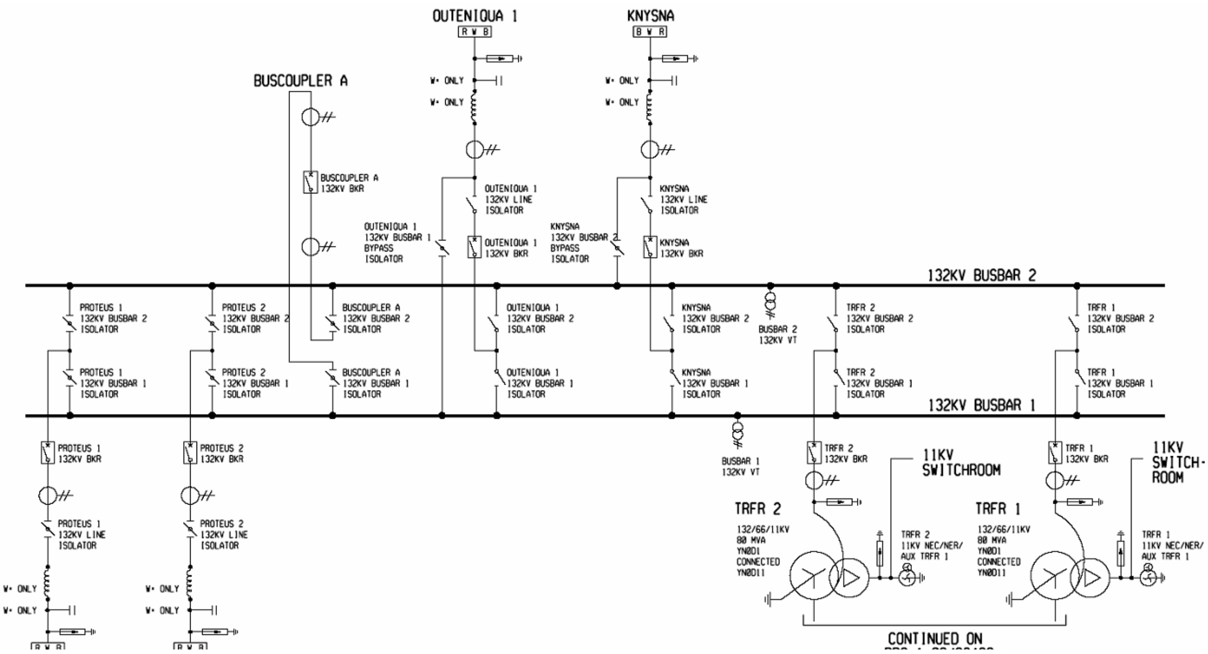


Figure 1.7: Single line diagram of a typical 132 kV substation.

(a) (b)

Figure 1.8: Typical 132 kV substations: Outdoor (a) and Indoor GIS (b)

1.2.4 Power lines and cables

High voltage feeders in the form of overhead power lines or underground cables interconnect high voltage substations. Typical high voltage overhead power lines are shown in Fig. 1.9.

(a) (b) (c)

Fig. 1.9: Typical overhead high voltage lines: (a): 400 kV suspension tower, (b) 400 kV double circuit strain tower and (c) 22 kV woodpole distribution line with fused cable connection.

(a) *(b)*

Fig. 1.10: New designs of (a) a 400 kV line and (b) a 132 kV line

When a new power line is planned, it is necessary to negotiate a servitude or “right of way”. Due to environmental considerations it is becoming increasingly difficult to obtain servitudes for overhead lines. In urban areas it is often necessary to use underground cables at voltages of 66 kV and below. The cost of underground cables is typically three times that of comparable overhead lines. At higher voltages cables are used only in special circumstances as the cost thereof is prohibitive.

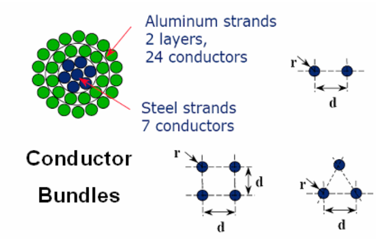
1.3 Basic Equipment

In this section the components of the power system, consisting of transmission and distribution substations and power lines, are discussed.

1.3.1 Power lines: towers, conductors, metal ware and insulators

As shown in Fig. 1.9 and Fig. 1.10, power line towers (pylons or poles) take on the form of steel lattice structures or wood or steel poles.

Typically, conductors are aluminium core steel reinforced (ACSR) as shown in Fig. 1.11. These conductors are often used as bundle conductors where two or more conductors are used in parallel as shown in Figs. 1.11. Bundled conductors are used to minimise the electric field strength for corona purposes as explained in section 2.19. As shown in Fig. 1.9, overhead shield wires are used on lines at transmission lines. The shield wires are used for lightning protection as explained in section 5.2.3(c).



(a)

(b)

(c)

Fig. 1.11: Examples of conductor power line components: (a) Detail of ACSR conductor, (b) Pistol grip connection of a conductor to a strain insulator and (c) Wind vibration dampers.

The line conductors are bare and the air clearances surrounding the conductors form the main insulation. Where the conductors are supported at the towers, insulators are used. Obviously the insulators must be manufactured from a good insulating material and must be of sufficient length to provide the necessary air clearance. The interface between the insulator and the air is very important, especially when the surface is contaminated (see section 3.3.2(d)).

Traditionally the ceramic materials glass and porcelain were the main insulator materials, but nowadays various non-ceramic materials are available. A number of different insulator constructions and materials are detailed in Fig. 1.12.

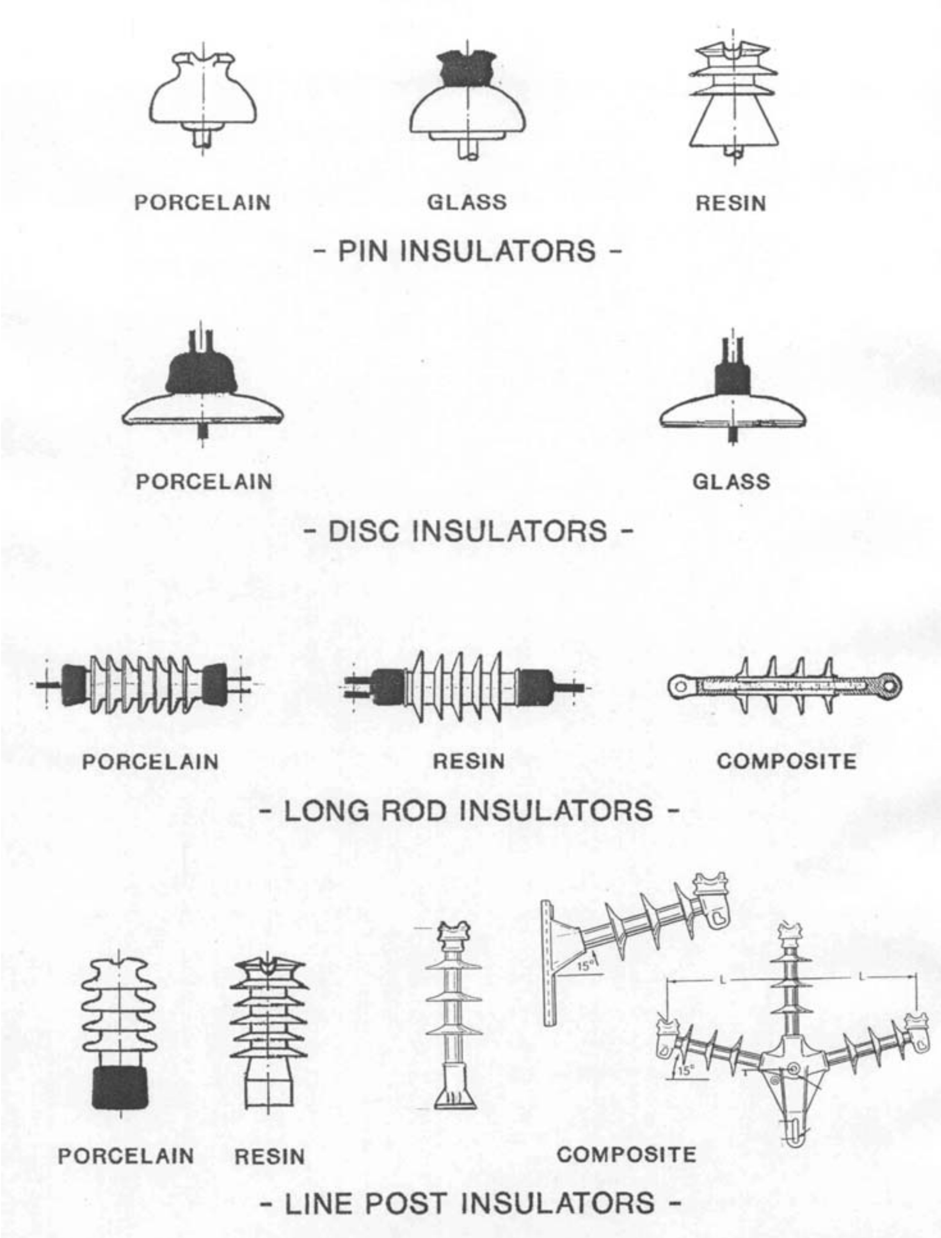


Fig. 1.12: Insulator types

1.3.2 Underground power cables

Underground cables are buried in trenches and correct installation is important from a safety point of view. Heat dissipation is also an important factor, as is explained in section 3.2.4(a).

At distribution level, the traditional oil impregnated paper has, to a large extent, been replaced by polymeric insulating materials such as polythene. Some cable constructions are shown in Fig. 1.13.

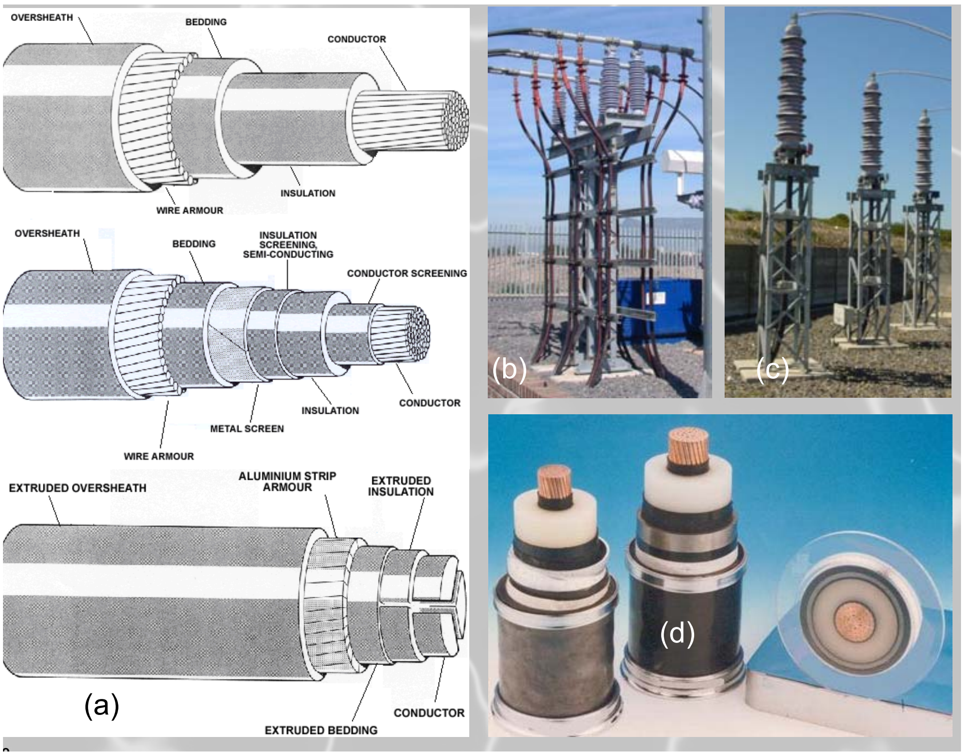


Fig. 1.13: Various types of cable constructions and terminations.

1.3.3 Bushings

It is sometimes required to take a high voltage conductor through a wall or the tank of a transformer. In such cases a bushing is required to support the high voltage conductor and to provide the necessary insulation in the axial and the radial directions. In Fig. 1.14 (a) a porcelain or resin bushing is used for this purpose. In this case the voltage distribution is non-linear in both the axial and radial directions. The voltage gradient is also high close to the high voltage conductor and this could cause discharges in those regions. The use of conducting cylinders inside the bushing results in a more uniform voltage distribution as is shown in Fig. 1.14 (b).

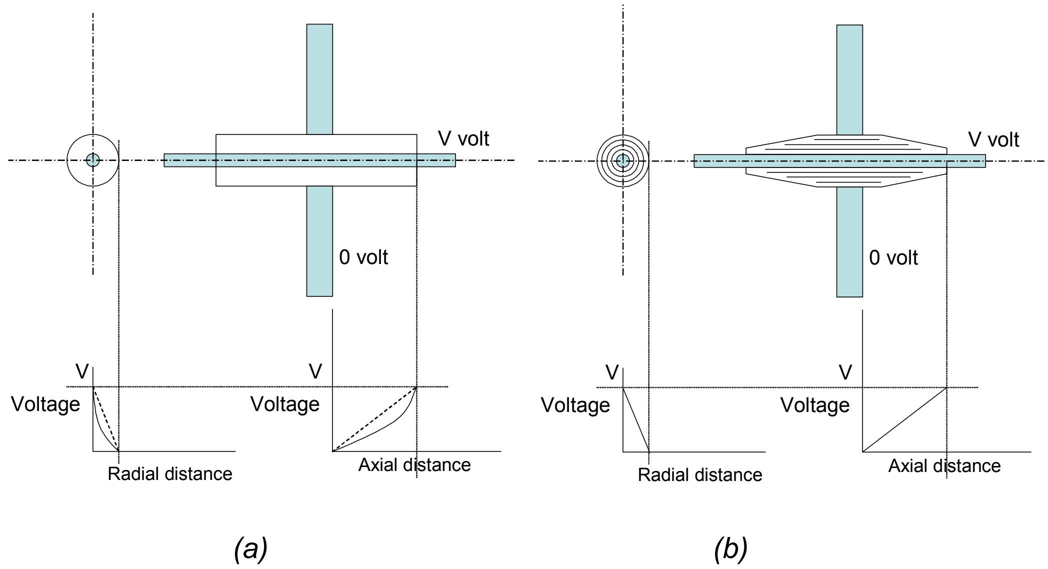


Fig. 1.14: Normal straight through epoxy resin bushing and (b) capacitively graded paper and oil bushing.

Examples of typical bushings are shown in Fig. 1.15.

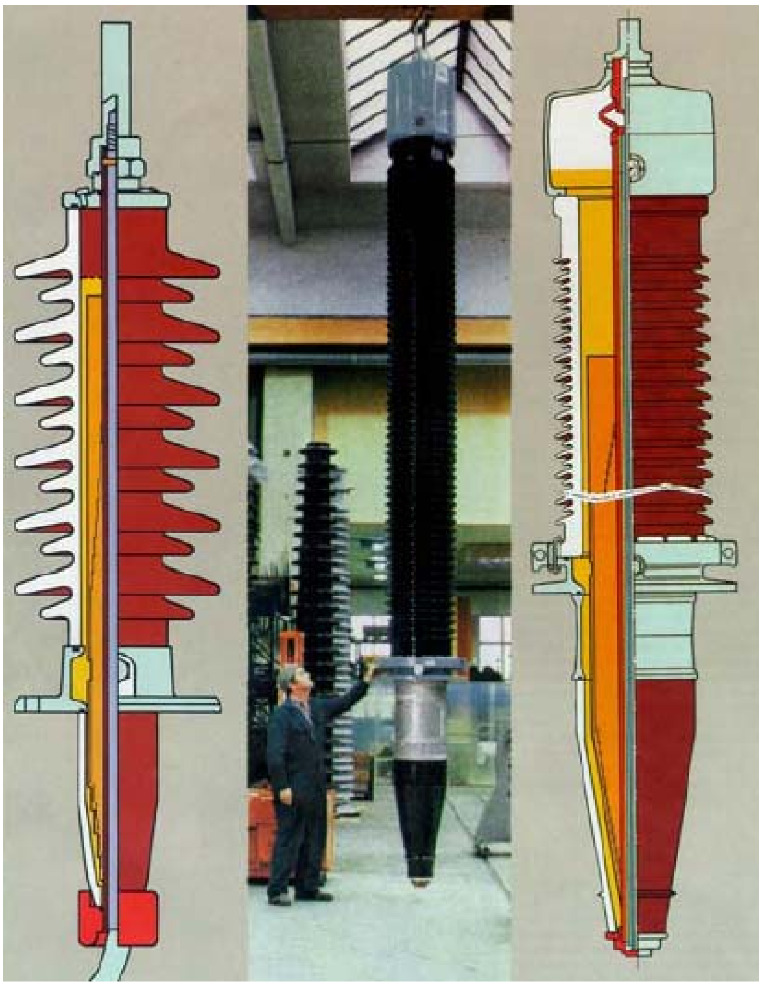


Fig. 1.15: Examples of typical graded bushings

1.3.4 Power transformers

The power transformers transform the voltage from one level to another and must be able to handle the full power to be transformed, i.e. the copper windings must be rated to handle the full load current and short time overcurrents and the magnetic circuit and insulation must be able to cope with the rated system voltage, allowing for overvoltages.

The copper windings must be adequately insulated to prevent insulation failure to the earthed iron core, between windings and inter-turn. Traditionally paper and linen tape around the windings, inside the tank, filled with oil, is used. The oil fills possible voids, while also serving as coolant that can circulate by natural convection or being pumped. Hard paper cylinders are used as part of the insulation system to prevent fibre-bridge flashover of the oil.

A transformer is equipped with a conservator to serve as an expansion tank to allow for the expansion of the oil when the transformer temperature increases. A silica gel breather sees to it that air entering from the atmosphere is dried.

Typical transformers are shown in Fig. 1.16.

Fig. 1.16: Power transformers

1.3.5 Instrument transformers: current transformers (CT's) and voltage transformers (VT's)

In an operating power system it is necessary to know the system voltages and currents as

accurately as possible. Current transformers (CT's), voltage transformers (VT's) and capacitive voltage tranformers (CVT's) are used for this purpose.
A VT is a high impedance shunt device, similar to a normal power transformer, whereas a CT is a low impedance device in series with the main current, as is shown in Fig. 1.17.

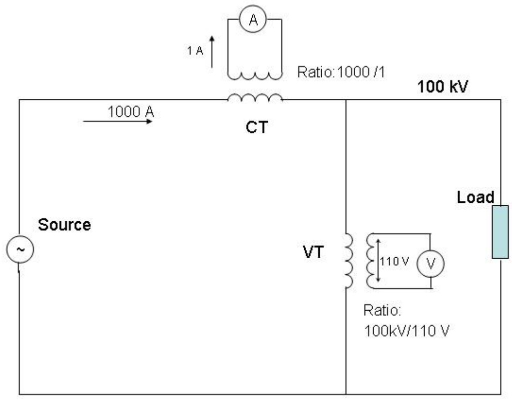


Fig. 1.17: Schematic diagram showing a typical application of current and voltage transformers to a single phase circuit

The active parts of both voltage and current transformers are similar, consisting of an iron core and two windings: a primary and a secondary. A VT is in fact identical to a power transformer with the primary connected to and rated for the high voltage, but has a very large ratio with the secondary voltage usually 110 V.

A typical rating for a VT is 100 VA. A CT on the other hand is applied in series with the main circuit. The primary usually consists of only one turn, carrying the current that has to be measured. The secondary winding is usually rated for 1 A. A typical rating for a CT is 10 VA.

Based on this, it is clear that, for a 1000/ 1 ratio the voltage across the secondary winding is 10 VA/ 1 A = 10 V and on the primary side 10 VA/ 1000 A, i.e only 0.01 V, a negligible voltage compared to the supply voltage.

Current Transformers

A typical design of a high voltage current transformer, such as is encountered in transmission substations, is shown in Fig. 1.18.

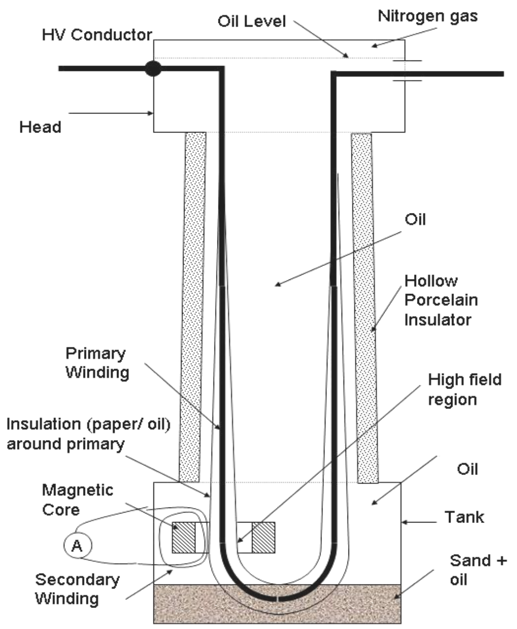


Fig. 1.18: Schematic diagram, showing the construction of a high voltage current transformer.

At medium voltages, such as those encountered in indoor distribution switchgear, the bar primary winding, the magnetic core and secondary winding are cast in epoxy under vacuum to remove all gas bubbles that may cause partial discharges (see section 3.3.2(a)).

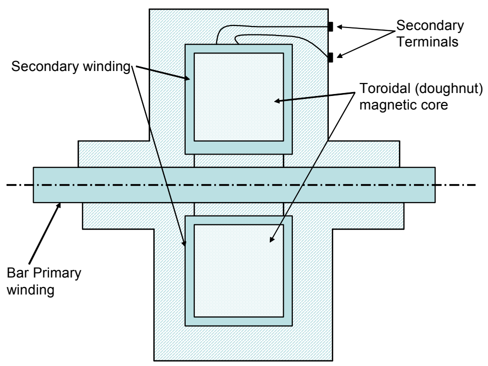


Fig. 1.19: Epoxy resin encapsulated current transformer for use in medium voltage switchgear

An important aspect relating to current transformers is that the lower the secondary impedance the better its performance. The secondary winding should always not be open circuited while the primary winding carries current. If this happens, high voltage spikes develop across its secondary terminals. As shown in Fig. 1.20, a CT can be modelled approximately by the magnetising impedance in parallel with the secondary loads.

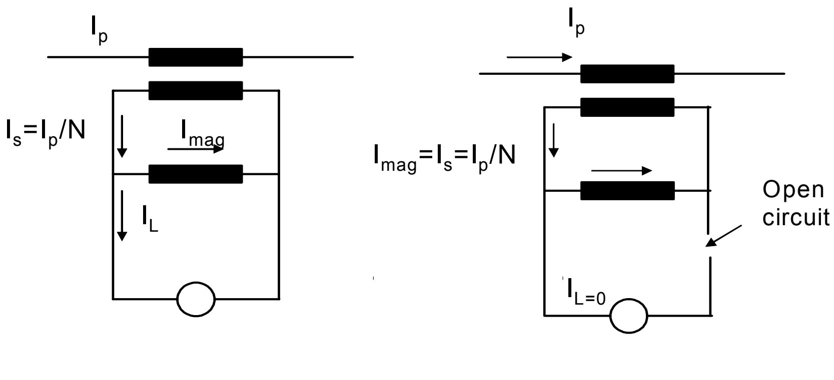


Fig. 1.20: Equivalent circuit of current transformer (a) normal operation and (b) with open-circuited secondary.

Since the CT is in series with the main circuit, a current source of I_p/N feeds the equivalent circuit, I_p being the primary current and N the CT ratio. Open circuiting the secondary circuit forces this full current through the magnetising impedance as the change in impedance presented by the open circuit of the CT secondary is too small relative to that of the load as to affect the primary current. As shown in Fig. 1.21, this forces the CT deeply into saturation.

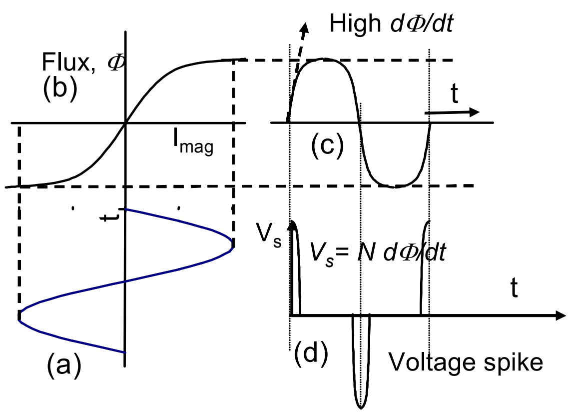


Fig. 1.21: CT with open-circuited secondary circuit: (a) secondary (magnetising) current vs. time, (b): magnetising characteristic, (c) CT flux vs. time and (d): secondary voltage spikes.

The resulting magnetic flux waveform is flat-topped with steep gradients (high values of $d\Phi/dt$ near the voltage zero crossings). In accordance with Faraday's Law, large voltage spikes appear across the secondary terminals of the CT. Ironically a current measuring device can produce very high voltages that do not originate from the system high voltage. These pulses may cause serious shocks to workers and may damage the insulation of the secondary winding and of equipment connected to it.

The magnetising reactance is also the main factor affecting the accuracy of current transformers.

Voltage Transformers

As already mentioned, VT’s are similar to power transformers, except that the ratio is so large as to produce a secondary voltage of typically 110 volts for measuring, metering and protection purposes. Whereas efficiency is of prime importance for power transformers, the accurate representation of the primary voltage is of concern in the case of VT’s.

At transmission voltages the active components are often mounted in a tank, onto which a bushing is mounted. At medium voltage levels the voltage transformers are often encapsulated in epoxy resin and the device is mounted inside the metal-clad switchgear cubicles.

Capacitive voltage transformers (CVT's)

As it is unpractical to design and manufacture a transformer with a very large ratio, such as is required for voltages of 275 kV and above, capacitive voltage dividers are used to first divide the voltage down to a lower voltage level before using a conventional voltage transformer. To compensate for the error and phase shift, caused by the capacitive divider, a series inductor L is provided. A typical CVT and a circuit diagram are shown in Fig. 1.22.

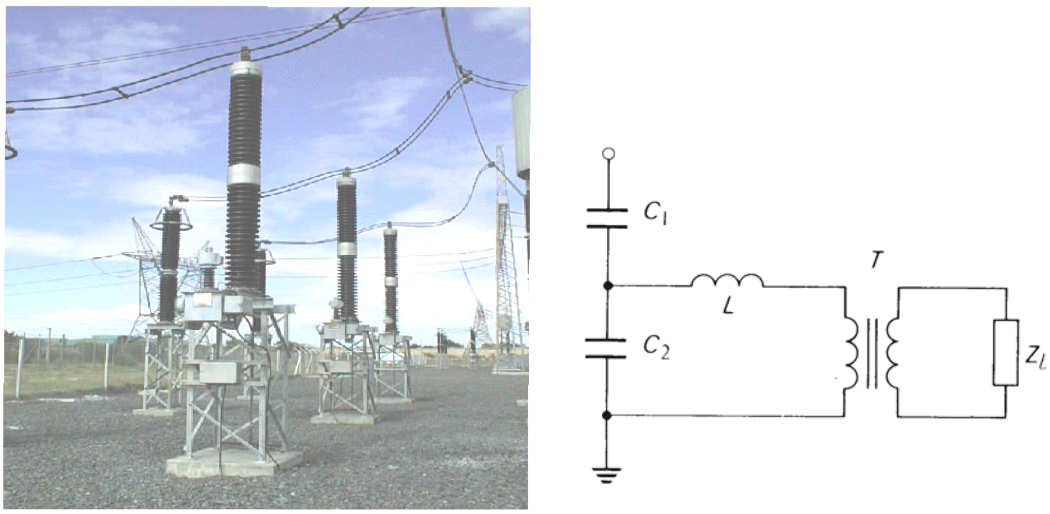


Fig. 1.22 :A high voltage Capacitive Voltage Transformer(CVT)

1.3.6 Line traps (LT's)

Power lines are also used to carry high frequency signals of the order of 300 kHz in power line carrier applications, such as voice communication or inter-tripping signals of line protection schemes. The high voltage capacitors of the CVT's are used as coupling capacitors and air cored inductors (line traps) are used as part of the filter circuits as shown in Fig. 1.23.

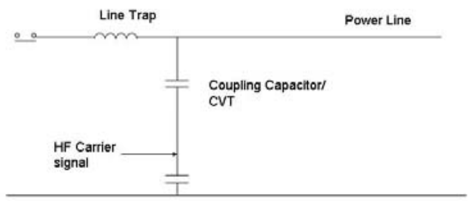


Fig. 1.23: Power Line Carrier coupling

Typical line trap are shown in Fig. 1.24.

Fig. 1.24: Typical Line Traps

1.3.7 Circuit breakers and fuses

The duty of circuit breakers and fuses is to rapidly interrupt fault current. When a short circuit occurs on the power system, currents of the order of tens of thousands of Ampere flow. A fault on the power system is usually caused by failure or breakdown of the insulation of some equipment on the power system. Often the fault current is caused by

air breakdown due to overvoltages, typically caused by system disturbances by factors such as lightning. These discharges develop into arcs, providing a path for the power frequency follow current. The physics of air breakdown will be treated in Chapter 3 and overvoltages are discussed in Chapter 5.

The presence of these power frequency fault currents are detected by the protection relays and the output contacts of the relays energize the circuit breaker trip coils, as shown in Fig. 1.25. The trip coils activate mechanisms that release stored energy (usually a charged spring) to force the contacts apart to interrupt the current. This is an onerous task and the arc quenching is assisted in various ways, depending on the type of circuit breaker. With AC circuit breakers arc interruption is assisted by the presence of current zero crossings. The interruption of DC arcs is more difficult.

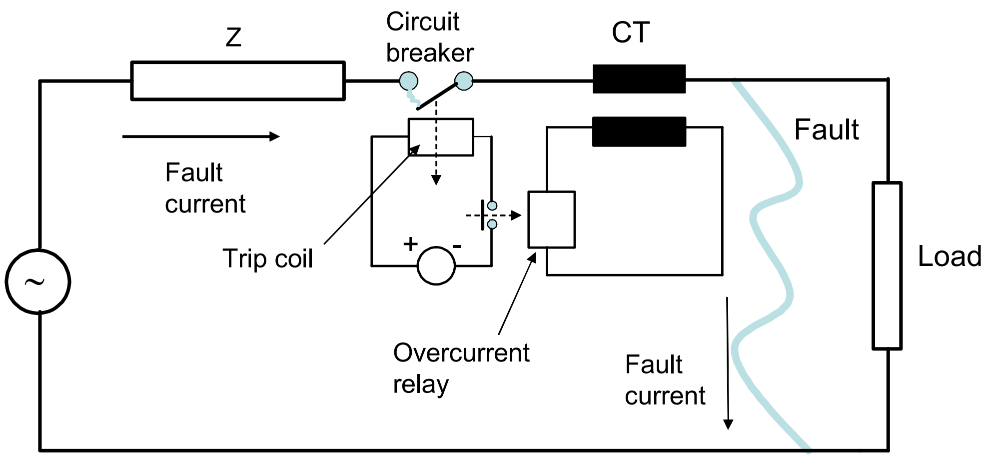


Fig. 1.25: Schematic presentation of the interruption of fault current by a circuit breaker and associated protection relays.

In the case of ac transmission lines, many of the faults (especially earth faults) are non-permanent and after a trip the circuit breaker recloses automatically. Often the ionization in the arc path has dispersed by the time the circuit breaker recloses and the circuit breaker remains closed.

In *air-break circuit breakers*, such as used in LV (< 100 V) and MV (up to 11 kV) systems, the contacts are in air at atmospheric pressure and the arc is quenched by the elongation, often assisted by magnetic blow-out coils, the short circuit current creating the magnetic field (see arc interruption in section 3.1.8). The arc is forced against arc chutes that cool and subdivide the arc. Nowadays, this type of breaker is rarely used at higher voltages.
In *air blast circuit breakers* compressed air at pressures as high as 1 MPa is used to blow

out the arc as the contacts are separated. The movement of the contacts are also effected by the compressed air. While the contacts are open, full system voltage appears across the contacts and the required insulation is provided by the pressurised gas (see Paschen's Law in section 3.1.5). Several (up to six) interrupting chambers, each housing a pair of contacts, are connected in series to share the voltage among the various interrupter heads. To ensure that this division is evenly, grading capacitors are provided over the contacts. Air blast circuit breakers have been used at 400 kV, but have been superseded by SF_6 circuit breakers for new projects. A typical 400 kV air blast circuit breaker is shown in Fig. 1.26.

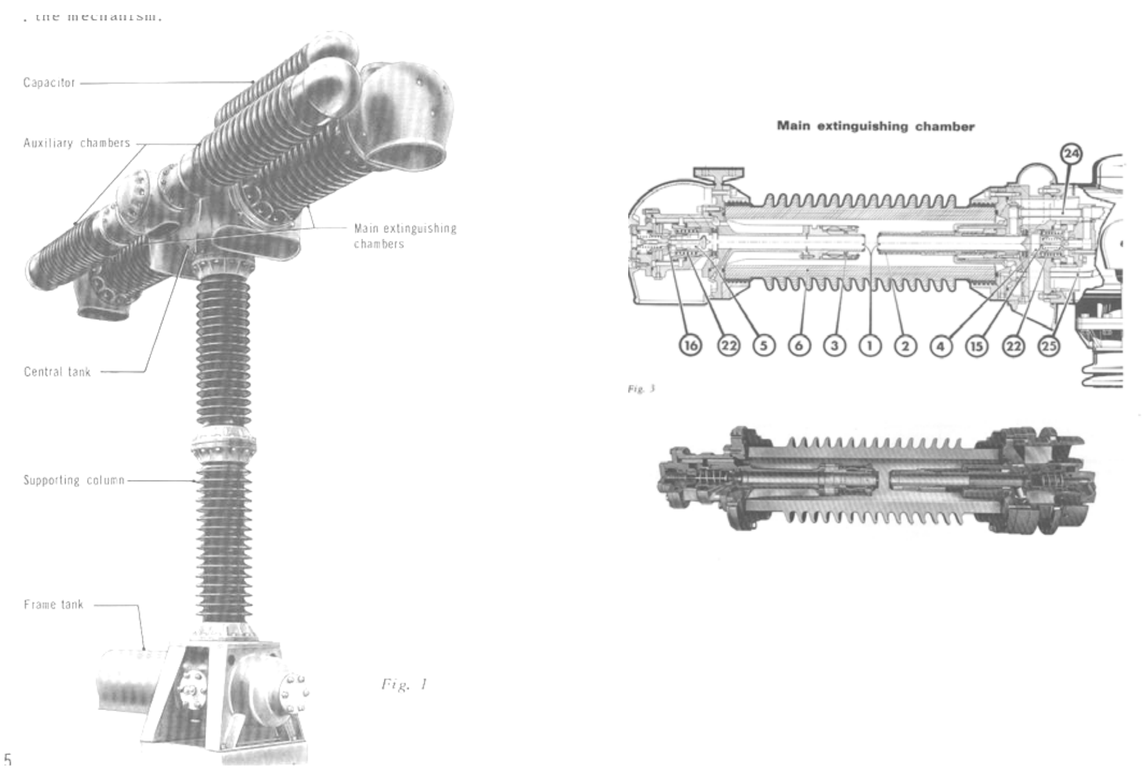


Fig. 1.26: Air Blast Circuit Breakers

In *oil circuit breakers* the interrupter heads are filled with mineral oil. With the contacts open, the insulating properties of the oil provide the insulation. In event of a fault the contacts move apart and an arc is drawn. The oil between the contacts absorbs the heat from the arc as it becomes a gas and so assists in the quenching process. When the alternating fault current goes through zero, cool oil flows back into the contact gap and finally interrupts the arc. The interrupting chamber is designed so as to control the gas and oil flow and to assist the arc extinguishing process (Fig. 1.27). Grading capacitors are also employed on units with multiple interrupting chambers. Oil circuit breakers have

been applied at all voltages up to 275 kV, but have been superseded by SF6 circuit breakers.

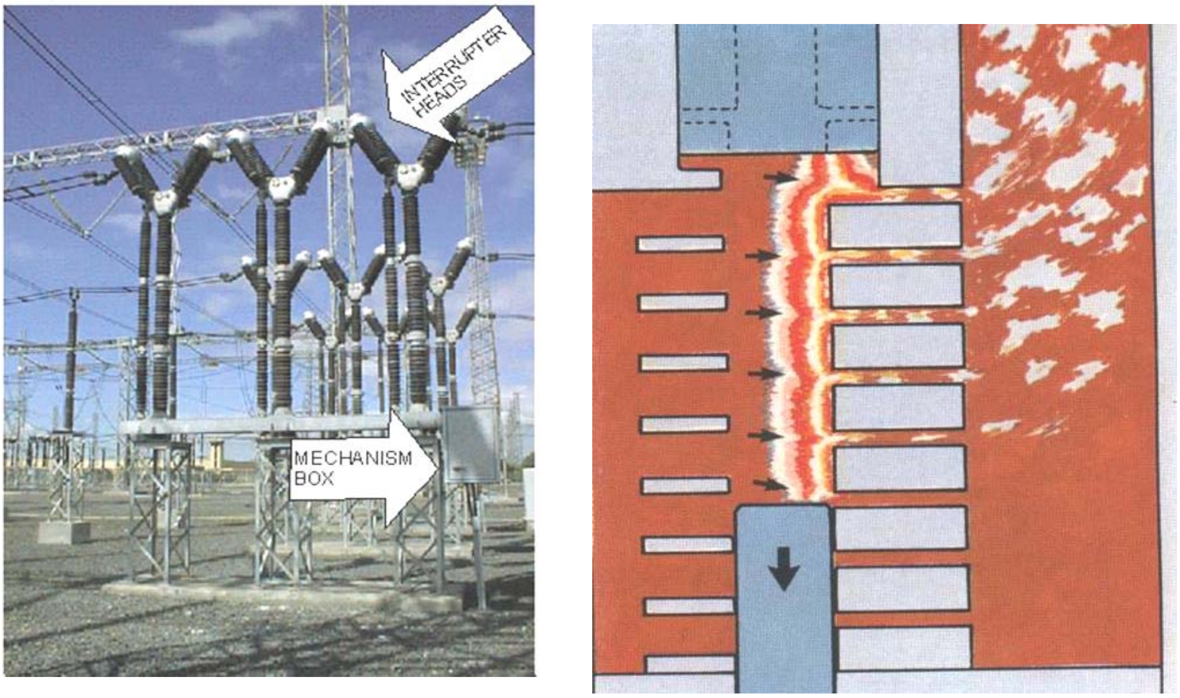


Fig. 1.27: Oil Circuit Breakers

In SF_6 *(sulphurhexafluoride) circuit breakers* the insulation and arc quenching functions are both performed by the SF_6 gas. SF_6 is an electronegative gas with superior insulation characteristics (see section 3.1.2). The gas also has the ability to assist arc quenching, due to its thermal and electronegative properties. The gas is kept in a closed cycle, i.e. not released to the atmosphere. The circuit breakers are usually spring operated. SF_6 circuit breakers are available for all voltages and are used for new projects.

Grading capacitors are also employed on units with multiple interrupting chambers, as is shown in Fig. 1.28.

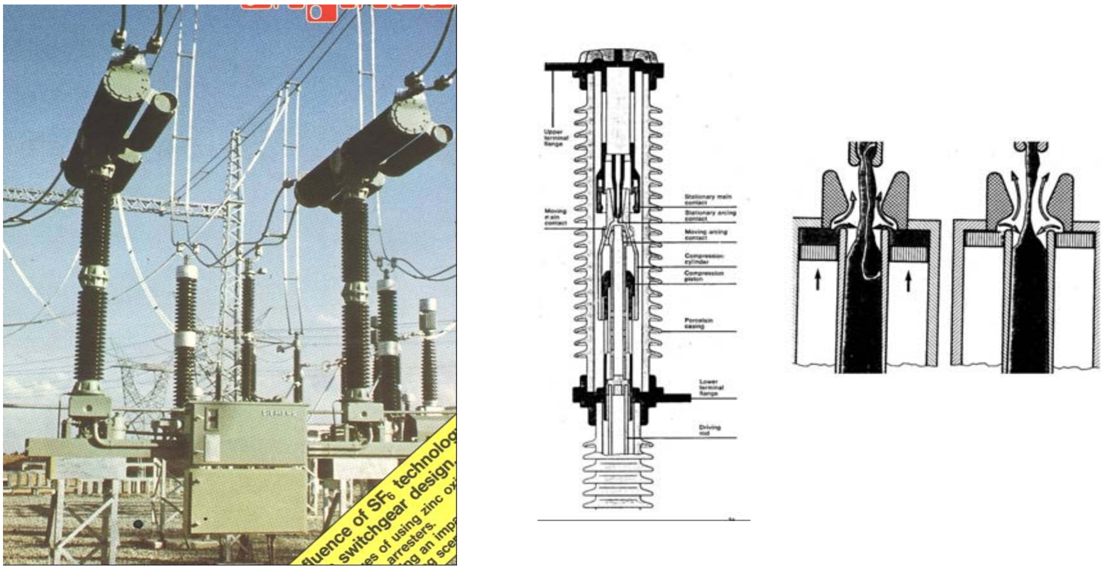


Fig. 1.28: SF6 Circuit Breakers

In *vacuum circuit breakers or contactors* the contacts are in a closed container with a very high vacuum (less than 10^{-7} mm Hg pressure). The vacuum prevents flashover when the contacts are open (Paschen's curve, Fig. 3.5). As the contacts move apart to interrupt the current is sustained and a metal vapour arc is formed, originating from the contact metal. At or near the current zero the vapour condenses on the contacts and vapour shield, thus interrupting the current. Vacuum circuit breakers and contactors are only used at lower voltages (< 30 kV). They also tend to chop the current before zero, causing overvoltages that may damage motor insulation. The principle of vacuum current interruption and a typical vacuum circuit breaker is shown in Fig. 1.29.

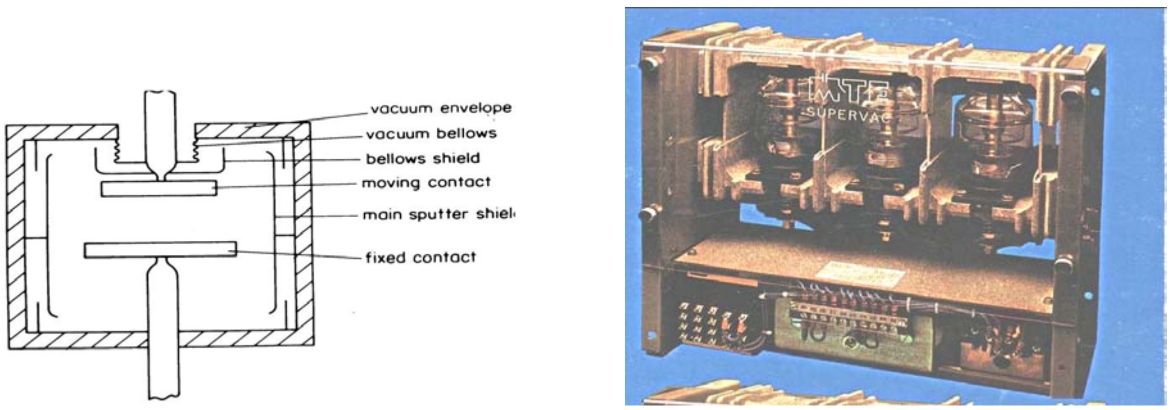


Fig. 1.29: Vacuum Circuit Breakers

Fuses are mainly used at voltages up to 22 kV. High rupturing capacity (h.r.c.) fuse elements are used. The fuses are often pole-mounted as drop-out fuse link assemblies. A typical arrangement is shown in Fig. 1.30.

(a) *(b)*

Fig. 1.30: (a) Cut-out (drop-out) Fuse assembly (b) Isolator (link) assembly

1.3.8 Isolators[2]

When working on apparatus, such as circuit breakers, it is necessary to disconnect the apparatus from the live system and to apply visual earths. For this purpose isolators and earthing switches are provided. Isolators differ from circuit breakers in that they should only be operated under no-load as they have no arc rupturing capacity. Fig. 1.31 shows the rotating type of isolator.

(a) *(b)*

Fig. 1.31: Typical rotating arm isolators: (a) Isolator closed and (b) Isolator open.

[2] Note the difference between *isolators* and *insulators* (See p. 47)

1.3.9 Surge arresters or lightning arresters (LA's)

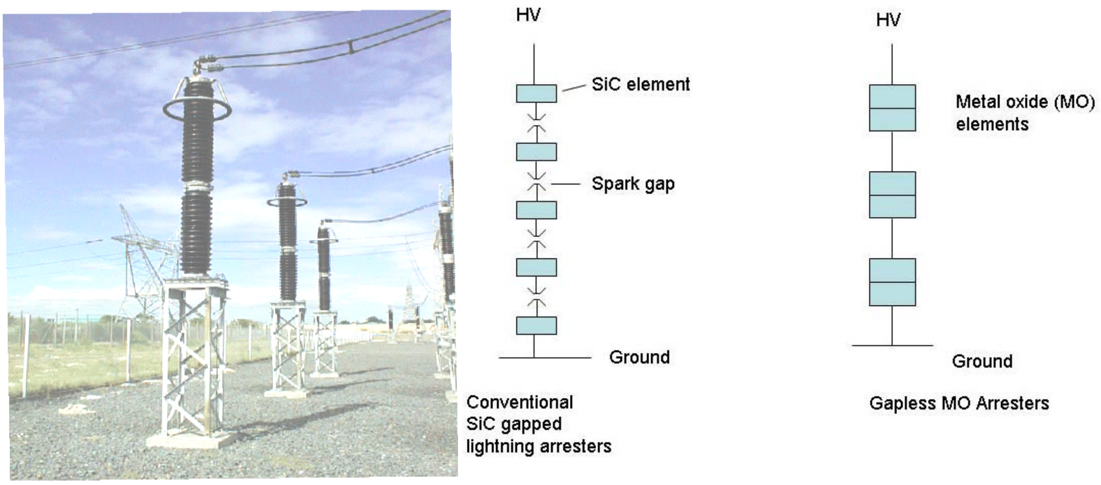


Fig. 1.32: Lightning Arresters

The power system is subject to transient overvoltages due to lightning and switching. Lightning arresters (also called surge diverters) are applied to limit the peak voltages to values that can not damage the equipment to limit overvoltages (see section 5.3). These overvoltages are limited by the use of nonlinear resistive elements. In conventional lightning arrestors silicon carbide elements were used. To prevent the continuous flow of leakage currents, spark gaps are required. Modern metal oxide elements low leakage currents that gaps are not necessary. Lightning arresters are usually fitted with grading rings to ensure a more uniform voltage distribution over the height of the arrester. This ensures that some internal elements are not more severely stressed than others.

1.4 Conclusion

In this introduction the state of the art of high voltage power systems has been summarised. High voltage technology is of paramount importance to facilitate the transmission and utilisation of large amounts of electrical energy. Knowledge of the performance of the various types of electrical insulation systems depend on the magnitude of the electric fields in the materials. In the next chapter concepts relating to electric fields and their calculation are discussed.

1.5 Review Questions

a) Compare the pros and cons of overhead lines and underground cables.

b) What is a bushing?

c) Which two purposes are served by the oil in a transformer? Elaborate.

d) What are the differences between CTs and VTs?

e) Why should the secondary of a CT never become open-circuited while it is energized?

f) Describe the concept of auto reclosing.

g) How does an isolator differ from a circuit breaker?

h) Describe the arc interruption processes in air blast, SF_6, oil and vacuum circuit breakers.

i) What are the pros and cons of AC and DC transmission?

2 FIELDS

Michael Faraday: The man who could visualise electro magnetic fields …

2.1 Introduction: Field concepts

A field is formally described as a spatial distribution of a quantity, which may or may not be a function of time. The concept of fields and waves is essential to describe what Michael Faraday called "action at a distance”. A typical example of such action-at-a-distance is gravitation: the fact that masses attract each other and that objects fall to earth. Since no mechanical bond exists between the objects, the concept of gravitational field is necessary to describe this force. Other examples of fields in nature are: thermal fields, the earth’s magnetic field and electrical conduction fields.

In high voltage engineering we are particularly interested in electric and magnetic fields. Electric fields are caused by the voltage difference between electrodes while magnetic fields are caused by currents flowing in conductors.

Electric fields are important in high voltage engineering due to the following effects:

- The performance of electric insulating materials is adversely affected by excessive electric field magnitudes. This is true for gaseous, liquid and solid insulating materials and these effects are described in Chapter 3.
- The presence of electric fields causes induced voltages on non-earthed objects underneath energised high voltage conductors. Similarly, the charge at the base of a thundercloud causes an electric field near the earth surface that may induce charge on objects such as transmission lines. Under dynamic conditions, when the charges vary with time, currents flow in conducting objects.

Magnetic fields do not have a direct effect on the properties of insulating materials but they affect the power system indirectly in the following way:

- High AC currents cause time-varying magnetic fields that induce voltages in conducting loops. Similarly, high time-varying currents due to lightning may cause induced voltages. These overvoltages cause high electric fields in power system components that may cause failure of the insulation systems.

The resulting overvoltages may also pose a threat to human safety (see Chapter 6.)

A time-varying electric field is accompanied by a magnetic field and vice versa, forming an electromagnetic field. This interaction prevails at higher frequencies and can be used to explain the propagation of travelling waves along transmission lines. These travelling waves are of importance in high voltage engineering as overvoltage surges, caused by lightning, are propagated along the lines.

2.2 Electrostatic Fields

The space around energised high voltage components is occupied by an electric field. The field has the same frequency as the voltage. The magnitude of these fields influences the behaviour of the insulation. It is therefore important to be able to estimate the electric field strength. The following sections discuss the methods available to analyse uniform and non-uniform fields.

2.2.1 Uniform fields

If a voltage difference exist between two parallel plate electrodes of large dimensions, the electrostatic field between the plates is uniform, as is shown in Figure 2 .1.

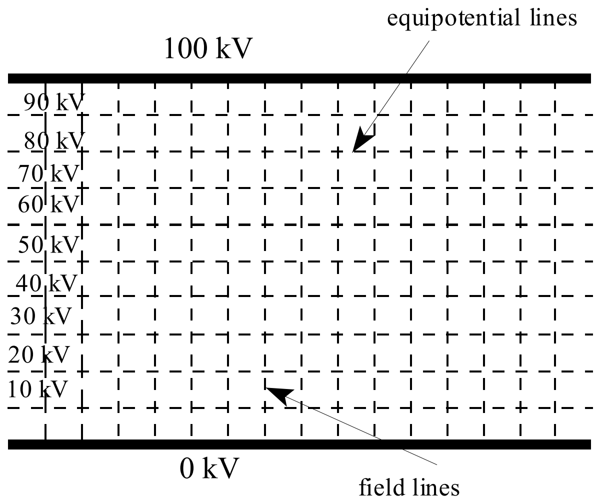


Fig. 2.1: Uniform Field

If 100 kV is connected between the plates, equipotential lines can be drawn as shown. If the distance between the plates is 10 cm, the electric field strength (intensity or gradient) is:

E = 100 kV / 10 cm = 10 kV/cm

In general, the electric field strength is given by:

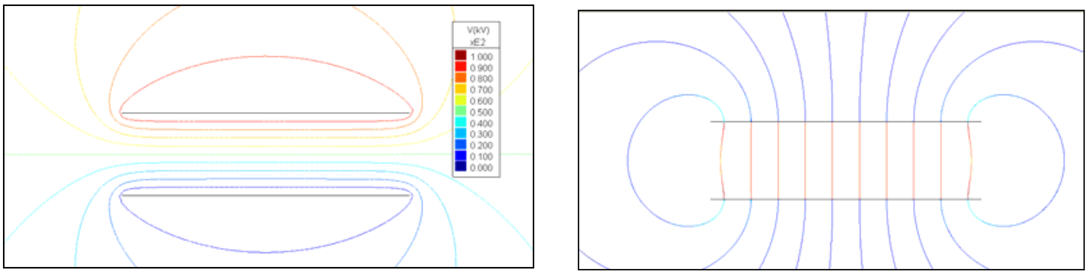
$$E = \frac{V}{d} \tag{2.1}$$

where V: voltage between plates

d: distance between the plates.

Note that the equipotential lines are equidistant and that the field strength E is constant throughout the region. The field is therefore a uniform field. The lines perpendicular to the equipotential lines are known as field lines. The field lines indicate the direction that a

positive charge would move if placed in the field. Note that the edge effects of the plates are ignored. If the edge effects are not ignored, the field strength will be higher at the sharp edges of the electrodes than in the central region, as shown in Fig. 2.2. The Rogowski "uniform field" gap is designed such that the field strength in the middle is $E_0 = V/d_0$, with d_0 the minimum distance between the electrodes. Elsewhere the field strength is less than in the middle ($E < E_0$). This is achieved by shaping the electrodes in such a way that they coincide with the equipotential lines obtained in Fig. 2.2, e.g. the 20% and 80% contours.



(a) (b)

Fig. 2.2: Edge effects in a parallel plate capacitors: (a) equipotential lines, (b) field lines

2.2.2 Non-uniform fields

a) Concentric cylindrical and spherical arrangements

If the electrodes are curved, the field strength is not constant throughout the region. In Figure 2.3 a section through a concentric cylindrical configuration is shown, as is used in SF_6 gas insulated systems. Note that the equipotential lines are much closer together near the inner conductor, resulting in higher field strength near the inner conductor. The field strength E is therefore not constant throughout the region and such a field is known as a non-uniform field.

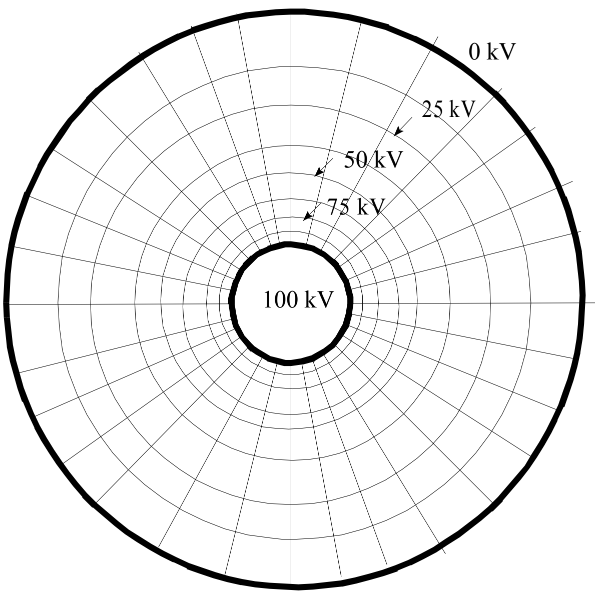


Fig. 2.3: Non-uniform Field

It can be shown that the electric field strength ar a distance r from the centre line of the configuration in Fig. 2 is given by:

$$E_r = \frac{V}{r\,ln(b/a)} \tag{2.1}$$

where V: voltage between the electrodes

b: outer radius

a: inner radius

r: distance from centre line

The maximum field strength occurs at the conductor surface, i.e. when $r=a$ in Eq. (2.1).
The field strength of two concentric spheres, with a voltage V between them, can likewise be derived, using Gauss's Law:

$$E = \frac{V}{r^2(1/a - 1/b)} \tag{2.2}$$

The maximum field strength occurs again at the surface, when $r=a$.
Note that for an isolated sphere, far removed from other objects, when $b=\infty$, Eq. (2.2) takes on a very simple form, i.e.

$$E = V/a \tag{2.3}$$

where a is the radius of the isolated sphere.
Note that for an isolated cylinder, on the other hand, such a convergence does not apply.

b) Cylinders and spheres: twin arrangements and conductors above a flat surface

Another practical arrangement that often occurs is that of a cylinder or a sphere with radius a at a height h above a flat conducting earthed plane as is shown in Fig. 2.4. Provided that the ratio h/a is large, the cylinders may be represented by a line charge on the centre line of the cylinder and the spheres by point charges at their centres, together with image charges as indicated in Fig. 2.4.

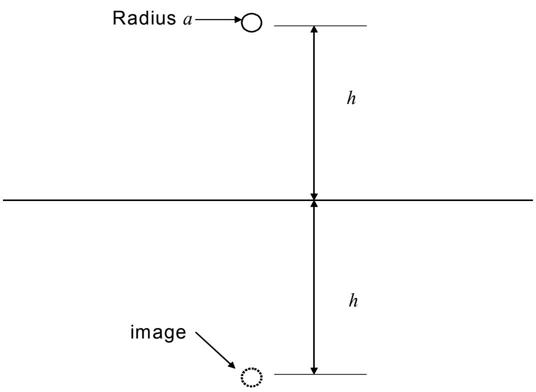


Fig. 2.4: Conductor above ground.

In the case of such a cylinder above ground, the maximum field strength (at the conductor surface) is given by:

$$E = \frac{V}{a\;ln(2h/a)} \tag{2.4}$$

The field strength at the ground surface, directly under the conductor, is given by

$$E = \frac{2V}{h\ ln(2h/a)} \qquad (2.4a)$$

Eqs. 2.1, 2.2, 2.3 and 2.4 can be very useful in practical situations as pointed out by the examples in the following exercises.

Exercise 2.1: Compare the field strength on the surface for a= 5 mm, b = 50 mm for the two-dimensional case (eq. 2.1) and three-dimensional case (eq. 2.2), respectively. Assume a DC voltage of 40 kV between the electrodes and calculate the maximum field strength for each case. Discuss. (Answer: Cylinders: 3.47 kV/mm, Spheres: 8.89 kV/mm – At the same voltage the surface field strength of the sphere is 2.3 times as that of the cylinder.)

Exercise 2.2: The outer cylinder of a 400 kV (line-to-line voltage) gas insulated concentric cylindrical arrangement has an 80 cm diameter. Determine the minimum diameter required for the inside conductor to limit the maximum gradient to 25 kV/cm. (16.8 cm. See graph below.)

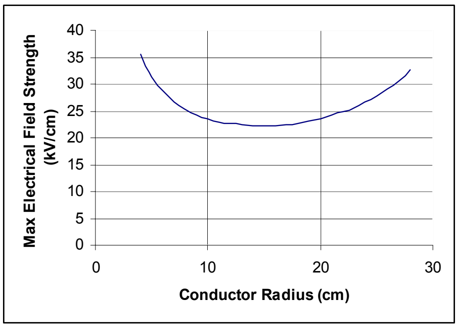


Fig. 2.5: Solution for Exercise 2.2

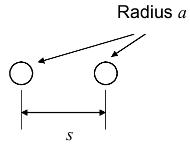
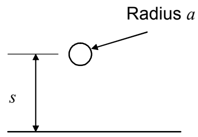
Exercise 2.3: An interesting practical problem is when the outside radius (b) is fixed, b = 10 cm, say, and the inner radius (a) is variable. What value of a gives the lowest maximum field strength? Consider two concentric cylinders such as a cable and two concentric spheres. What is the optimum b/a ratio for each case? Take V = 100 kV DC. Use calculus or trial and error. (Answer: Cylinders: b/a = e= 2.718, Spheres: b/a = 2)

If the two cylinders or spheres are too close together or too close to the plane, it is inaccurate to represent the conductors by charges at their centres. In such cases proximity effects must be taken into account. Schwaiger [8] analysed such cases and produced relationships to deal with a variety of cases. He produced tables, expressing the maximum field strength, occurring at the surface of the conductor, in terms of a parameter:

$$p = (s + a)/a \qquad (2.5)$$

where s is the gap length and a the radius. His work has been incorporated in the regression equations given in Table 2.1. The accuracy of these formulae is better than 4%.

Table 2.1: Maximum field strengths for various arrangements

		
	$p = (s/2 + a)/a$ (2.5a)	$p = (s + a)/a$ (2.5b)
Cylinders	$E_a = \dfrac{1}{ln(2p)/p + 1.36\ e^{-1.52p}}\left(\dfrac{V}{s}\right)$ (2.6)	
Spheres	$E_a = (e^{-0.2(p-1)} + p - 1)\left(\dfrac{V}{s}\right)$ (2.7)	

Example: Approximations for complex configurations

Consider the configuration shown in Fig. 2.6, showing a rod-plane gap. The radii of the rod and the hemispheres are 10 mm and the voltage of the electrodes relative to the plane is 100 kV. In accordance with eq. 2.3, approximating the hemisphere by an isolated sphere, the maximum field strength would be 100/10 = 10 kV/mm.

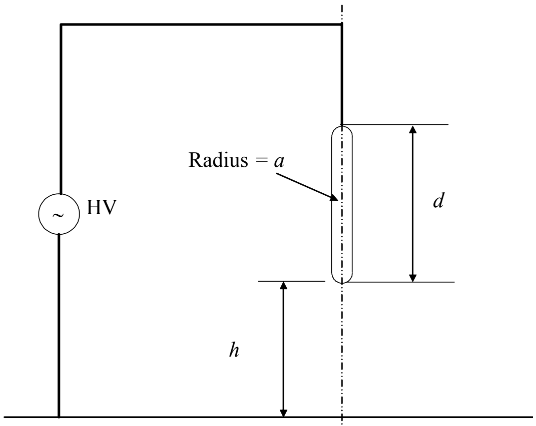


Fig. 2.6: Rod-plane gap

The configuration was simulated, using a boundary method field analysis package. Some results are given in Table 2.2. It will be noted that the values for d = 20 mm (sphere diameter) agree reasonably well with above value of 10 kV/mm, but for the case of d = 120 mm the limitations of the use of the spherical approximation in complex configurations are apparent.

Table 2.2 : Maximum field strengths: simulation results for the arrangement in Fig. 2.5

h **(mm)**	**Maximum field strength (kV/mm)**	
	d **(mm)**	
	20 (i.e. a 20 mm diameter sphere)	120
100	10.04	8.86
500	9.92	8
1000	10	7.84

d) The electric field strength of three phase lines

It is often necessary to know the electrical field strength under three phase lines or to know the maximum field strength at the surface of the conductors. In these cases the conductors are represented by line charges along their centre lines. These line charges are obtained for the specific configurations by inverting the potential coefficient matrix. Once the line charges are available, the magnitudes of the field strength contributions of each line can be computed, using the following equation:

$$E = \frac{q}{2\pi\varepsilon_0 r} \tag{2.8}$$

where

r: distance between point where the field strength is required and the conductor

q: line charge (C/m)

ε_0: absolute permittivity (F/m).

These contributions are summed as vectors, bearing in mind the phase difference between the various phases.

e) Capacitance formulae

Although not directly associated with the maximum field strength, the following equations can be derived for various configurations:

Two co-axial cylinders:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(b/a)} \tag{2.9}$$

A cylinder above a conducting plane:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(2h/a)} \tag{2.10}$$

Two concentric sphere (a sphere within a sphere):

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{(1/a - 1/b))} \tag{2.11}$$

An isolated sphere, far removed from other objects:

$$C = 2\pi\varepsilon_0\varepsilon_r a \tag{2.12}$$

In these equations:

a: inside radius in m

b: outside radius in m

h: height above the surface in m

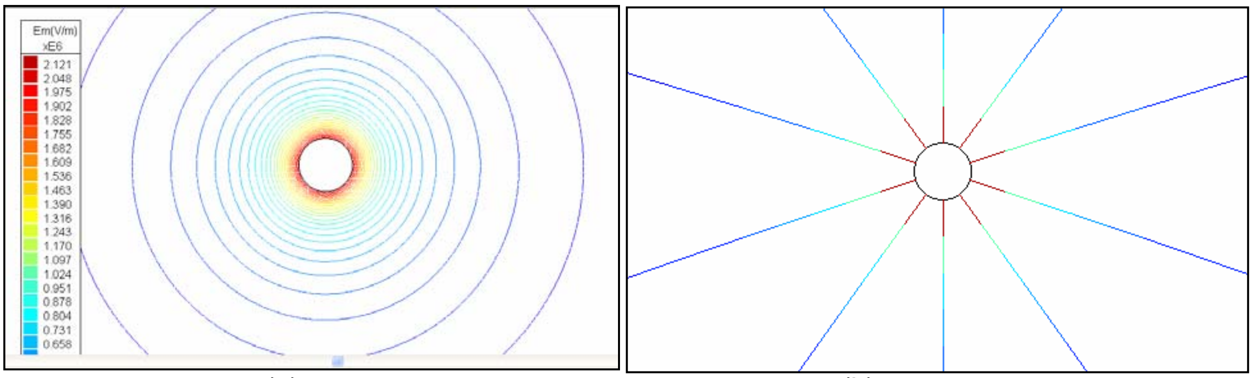
ε_0: absolute permittivity F/m

ε_r: dielectric constant

2.2.3 Bundle conductors and grading

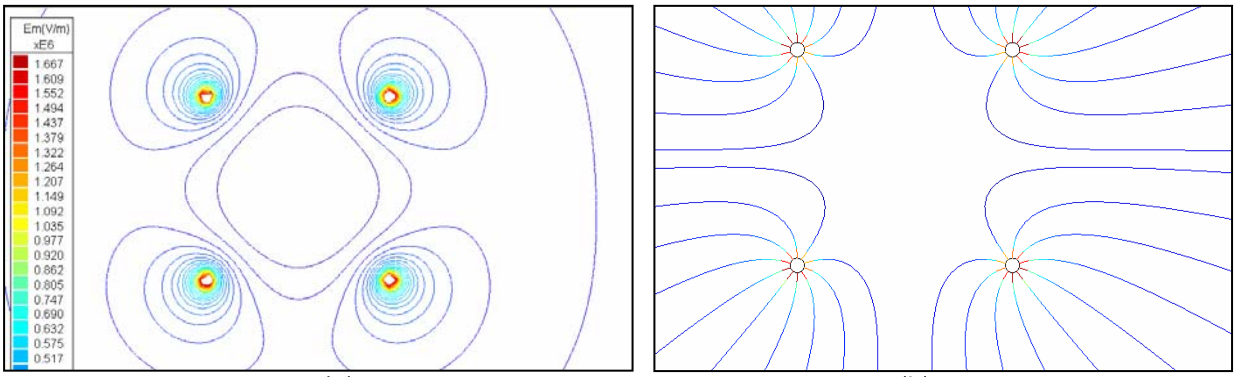
One of the key aspects of high voltage engineering is to be able to control or modify the E-field strength in order to minimise the risk of flashover or the occurrence of corona discharges or to obtain a more uniform field along a high voltage measuring divider or surge arrestor.

On transmission lines, bundled conductors, i.e. more than one parallel conductor per phase are used to improve the corona performance of lines. Fig. 2.7 and 2.8 show how the maximum stress is reduced by bundle conductors. Both conductor systems are energised at the same voltage.



(a) (b)

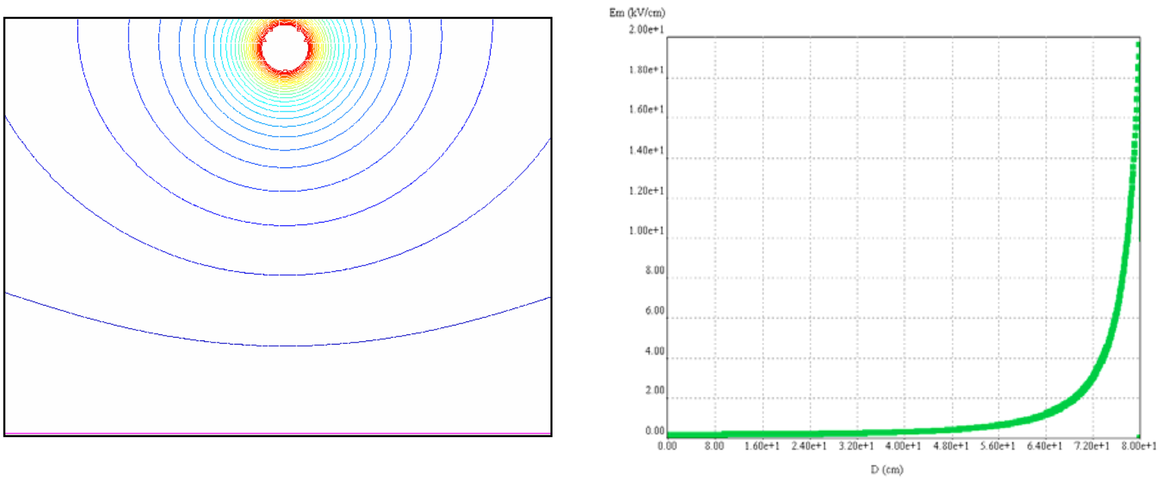
Fig. 2.7: Lines of constant E-field (a) and field lines (b) of a single conductor having a diameter of 40 mm, energised at 300 kV peak.



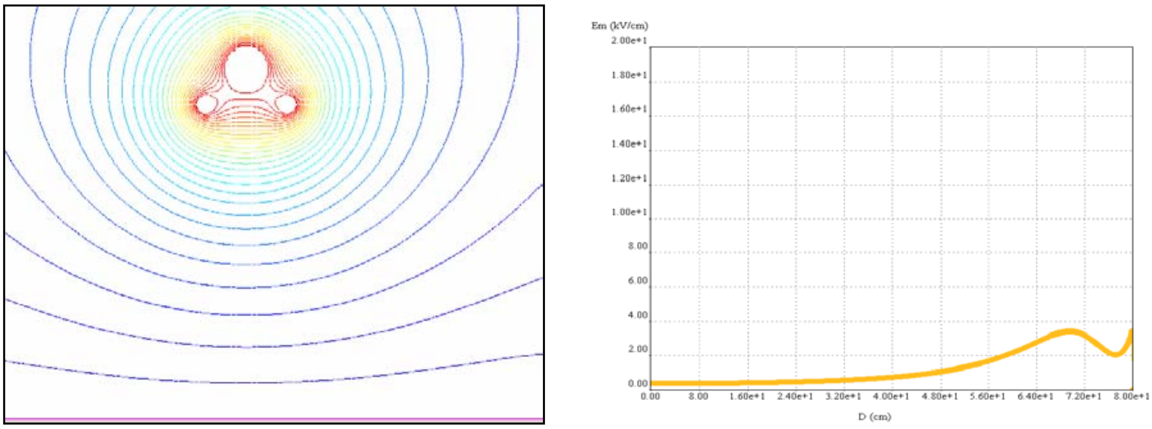
(a) *(b)*

Fig. 2.8: Lines of constant E-field (a) and field lines(b) of quad bundle conductors with the same cross-sectional area as the conductor in Fig. 2.5 – each conductor 20 mm diameter, spaced at 300 mm, energised at 300 kV peak.

Another case of field modification is in the application of stress-relief rings and grading electrodes, as shown in Fig. 2.9, in order to linearise the voltage distribution along a surge arrestor, for example



(a) (b)



(c) *(d)*

Fig. 2.9: The use of grading rings to linearise the voltage distribution along a high voltage apparatus: (a) and (b) without and (c) and (d) with grading rings

2.2.4 Mixed dielectrics

Thus far in this chapter only cases were considered where a homogeneous insulating material, e.g. air or a gas was used. Practical insulation systems such as transformers incorporate solid and liquid insulating materials together with air. In some instances unintentional gas or air voids exist in solid or liquid materials.

Solid and liquid insulating materials are classed as dielectrics, as they possess the property of polarization, giving them a dielectric constant larger than 1.0, as opposed to air and gases which have unity dielectric constants (See 3.2.1).

At an interface between two insulating materials, the components of the E-field parallel to the interface are equal in the two regions. The components of the E-field normal to the interface are, however, inversely proportional to the dielectric constants. These relationships are given in the following equations:

$E_{t1} = E_{t2}$ and $\varepsilon_1 E_{n1} = \varepsilon_2 E_{n2}$ (2.13)

where the subscripts t and n refer to the tangential and normal (perpendicular) components, respectively, and the subscripts 1 and 2 refer to the two materials.

The effect of these relationships can be seen in the two arrangements in Fig. 2.10. In both cases the surrounding material is air (ε_r = 1) and the other material is porcelain (ε_r = 6). It will be observed in these figures that, when the field lines cross the interface, the equipotential lines are closer together (i.e. the field is higher) in the material having the lowest dielectric constant (typically the air or gas region).

Another type of problem of this type is that of cylindrical and spherical discontinuities in a uniform gap as illustrated in Figs. 2.11 and 2.12. In these diagrams, the region with the lowest dielectric constant has more equipotential lines (a higher field strength) but more field lines (a higher flux). The equations are given in Table 2.3.

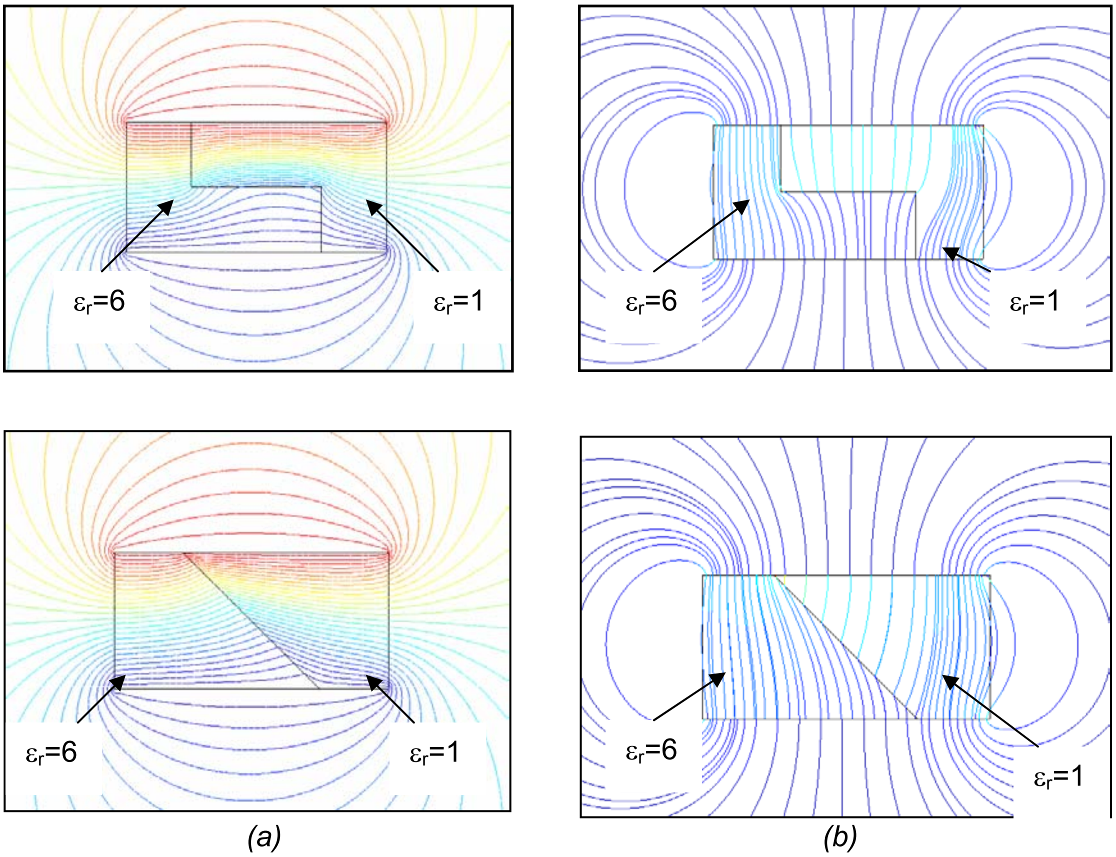
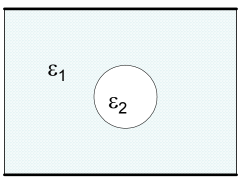
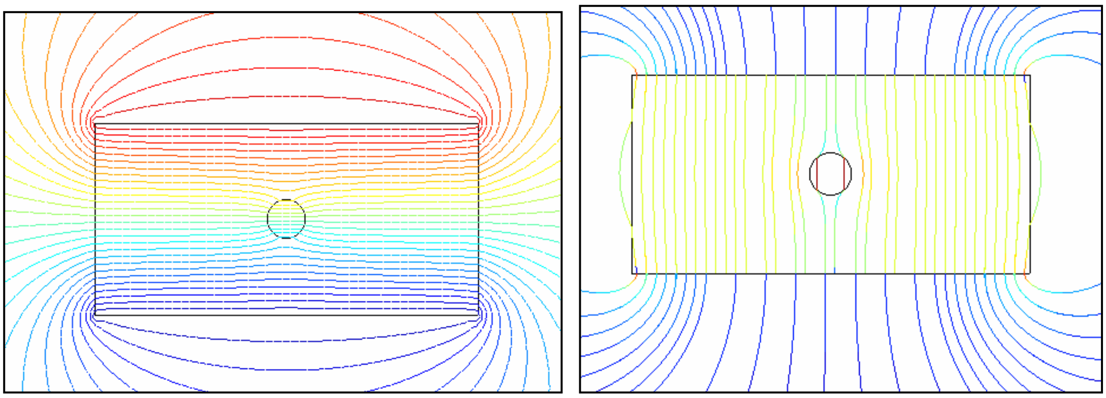


Fig. 2.10: Equipotential lines (a) and field lines (b) for two insulation systems consisting of two different insulating materials.

Table 2.3: Equations for field strength in cylindrical and spherical discontinuities

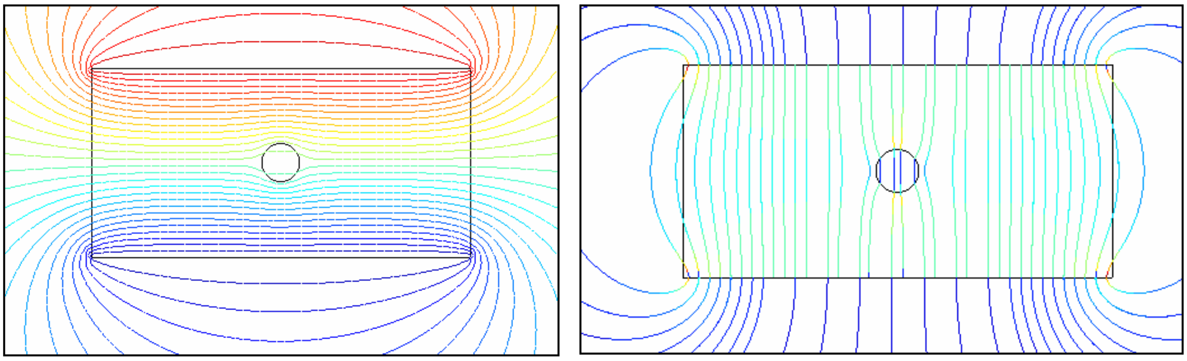
	Cylinder	**Sphere**
	$E_2 = \dfrac{2\varepsilon_1}{\varepsilon_1 + \varepsilon_2} E_1$ (2.14) If $\varepsilon_1 >> \varepsilon_2$: $E_2 = 2E_1$ (2.16) If $\varepsilon_2 >> \varepsilon_1$: $E_1 = 2E_2$ (2.18)	$E_2 = \dfrac{3\varepsilon_1}{\varepsilon_1 + 2\varepsilon_2} E_1$ (2.15) If $\varepsilon_1 >> \varepsilon_2$: $E_2 = 3E_1$ (2.17) If $\varepsilon_2 >> \varepsilon_1$: $E_1 = 3E_2$ (2.19)



(a) (b)

Fig. 2.11: Equipotential lines (a) and field lines (b) for a cylindrical void in a dielectric, having a dielectric constant of 6

This configuration of Fig. 2.11 demonstrates the problems associated with unintentional air or gas bubbles or spaces in solid insulation systems. The field strength in the gas bubble is enhanced and may cause breakdown of the gas, leading to partial discharges (see section 3.2.4(b)).



(a) (b)

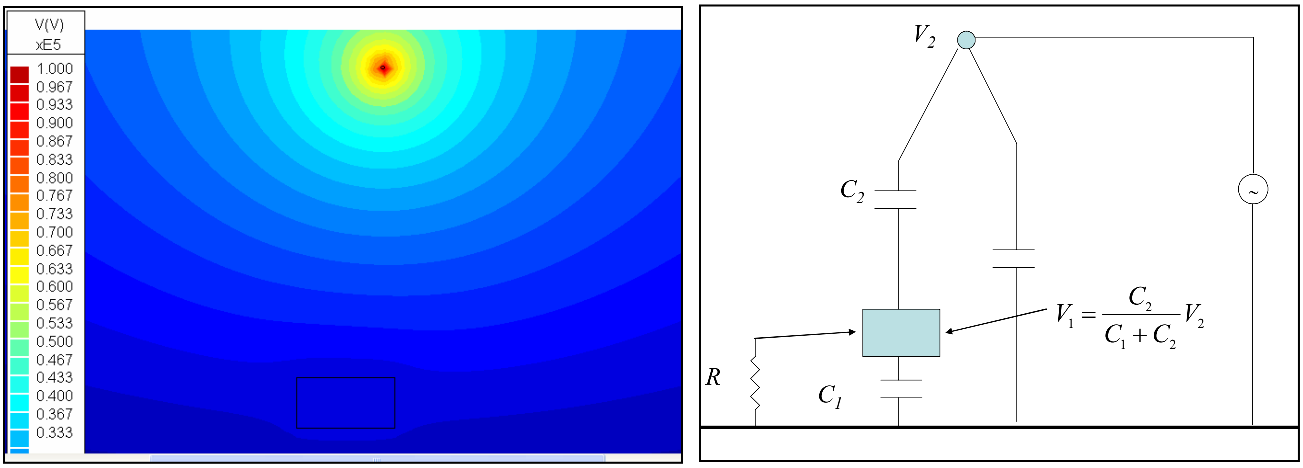
Fig. 2.12: Equipotential lines (a) and field lines (b) for a cylindrical sphere, having a dielectric constant of 6 in an air gap.

The configuration of Fig. 2.12 is similar to the case where a water droplet (ε_r = 80) finds itself in a high field - typically on the surface of a high voltage insulator. The field strength adjacent to the droplet is increased, leading to water droplet corona, initiating insulator ageing (see section 3.2.4(d)).

2.2.5 Capacitive coupling

An ungrounded object under a high voltage structure will adopt the potential of the equipotential surfaces in its vicinity as shown in the field simulation Fig. 2.13 (a). The phenomenon can also be explained as capacitive coupling, using a capacitive equivalent circuit as shown in Fig. 2.13 (b). Touching the object will put the resistance to ground of the body in parallel with C_1, allowing current to flow through the body. These currents are often small, as the capacitive Thévenin impedance of the circuit is high, but if the "floating object" is an ungrounded, unenergised conductor of an adjacent power line a lethal shock may result.

In the case of DC the capacitors will also be charged but will discharge completely when touched. Charge on a thundercloud will likewise induce charges on floating objects.



(a) *(b)*

Fig. 2.13: Electrostatic induction (a) and capacitive equivalent circuit (b).

2.3 Magnetic Fields

Whereas electric fields are caused by voltage, magnetic fields are caused by current. Magnetic field lines, indicating the direction of the field, form closed loops around the current carrying conductor that causes the field. The magnetic field lines of a conductor above ground are shown in Fig. 2.14.

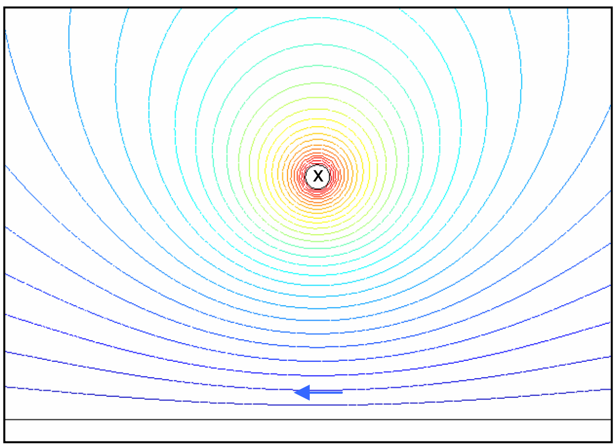


Fig. 2.14: Magnetic Field lines of a conductor above ground.

The magnetic flux density, B in tesla is given by:

$$B = \frac{\mu_0 I}{2\pi r} \tag{2.20}$$

with I: current in A

r: distance from conductor in m

μ_0: absolute permeability ($4\pi.10^{-7}$ H/m).

The field direction is given by the right hand rule as shown in Fig. 2.13.

2.3.1 Magnetic induction: inductive coupling

Faraday's Law forms the basis for the phenomenon of magnetic induction. This law states that a magnetic flux that varies with time induces a flux in any loop linking this flux. Consider the case of a time-varying current in a conductor above ground as shown in Fig. 2.15. If the effect of the return current is ignored, the current $i(t)$ causes a flux $\phi(t)$ as indicated, in accordance with Faraday's Law:

$$v(t) = N\frac{d\phi}{dt} \tag{2.21}$$

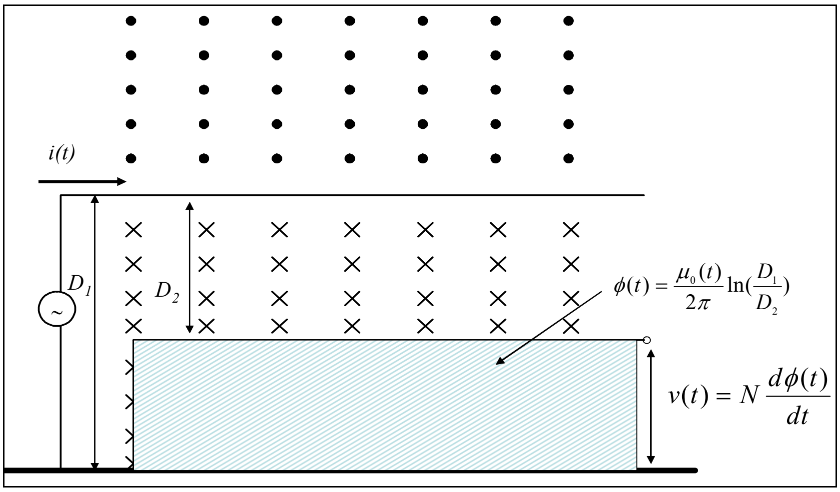


Fig. 2.15: Inductive coupling due to a current above ground.

Time-varying currents due to lightning also cause induced voltages in loops formed by reticulation and communication circuits, sometimes with catastrophic consequences.

2.4 Electrical Conduction Fields

Although not directly related, there exists a close analogy between conduction and electrostatic fields. The analogy can be summarised as indicated in Table 2.4.

Table 2.4: Analogy between electrostatic and conduction fields

Electrostatic Field	**Conduction Field**
Voltage difference, V, volt	Voltage difference, V, volt
Charge, Q, coulomb	Current, A
Stress, E, V/m	Stress, E, V/m
Capacitance ,C, farad	Conductance, G = 1/ R, siemens
Permittivity, $\varepsilon=\varepsilon_0\,\varepsilon_r$ F/m	Conductivity =σ = 1/ ρ , siemens/m

Based on this analogy, it can be shown that the field pattern between two concentric spheres will be identical to that of Fig. 2.2, also when the space between the electrodes is filled with a conducting substance with a resistivity in ohm metre. The resistance between the spheres can also be shown to be:

$$R = \frac{\rho}{4\pi}(1/a - 1/b) \qquad (2.22)$$

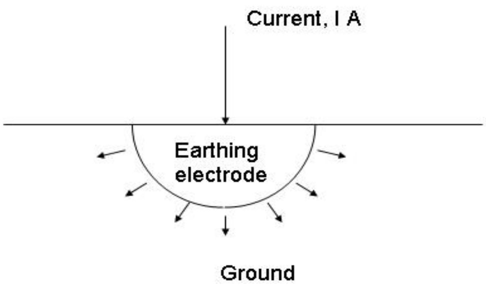


Fig. 2.16: Hemisphere as earth electrode

The resistance of a hemispherical electrode, shown in Fig. 2.16 with respect to "infinity" is obtained from eq. (2.8) by letting b $\to \infty$, i.e.

$$R = \frac{\rho}{2\pi a} \qquad (2.23)$$

In practice, driven rods are often used to obtain a low resistance to ground. Various formulae are available for different configurations. Typically, the earthing resistance of a rod of diameter d, driven into soil with a resistivity, ρ, to a depth of l, is given by:

$$R = \frac{\rho}{2\pi l}\ln(\frac{8l}{d} - 1) \qquad (2.26)$$

It is important to obtain a low earthing resistance and extensive earth mats are used for this purpose. A current I flowing into the electrode causes a voltage gradient along the surface of the soil that could be lethal, especially in the case of lightning currents. All transformer neutrals are connected to the earth mat, using conductors of sufficient cross

section, to conduct earth fault current. Power line pylons are also earthed to obtain a low resistance to limit the potential rise when of lightning current flows down the pylon.

Typical values of soil resistivity range from 10 (garden soil), 50 (clay), 100 (sand) to as high as 5 000 ohm metre for rocks. Moisture content reduces resistivity.

With rapidly changing currents, such as those associated with lightning, the inductance of the earthing system becomes important.

2.5 Thermal Fields

There is likewise an analogy between the electrical conduction field and the thermal field as is shown in Table 2.5.

Table 2.5: Analogy between electrical and thermal conduction fields

Electrical conduction field	Thermal conduction field
Current, I ampere	Heat (Power), P, watt
Voltage difference, V, volt	Temperature difference, T, degrees C or K
Electrical resistance, R = V/I ohm	Thermal resistance, R_t = T/P, °C/W
Resistivity, ρ, ohm metre	Thermal resistivity, t., °Cm /W
Capacitance, C, farad (coulomb/ volt)	Heat capacity, (joule/ °C)

This analogy is useful when considering the heating of cables and other equipment. Heating and cooling of a body is affected by the thermal time constant in analogy with the electrical RC time constant. These factors will be discussed together with solid insulating materials.

2.6 Health Effects

From time to time magazine or newspaper articles appear on possible health effects to people that live near transmission lines or high voltage workers. The 50 Hz electric and magnetic field limits set by the International Commission on Non-ionizing Radiation Protection (ICNIRP) are shown in Table 2.6.

Table 2.6: Maximum allowed Field strength levels:

Exposure	**E-Field (kV/m)**	**H- Field (μT)**
Occupational	10	500
Public	5	100

These limits are for 50/60 Hz time varying fields. The electric and magnetic field effects of DC lines on humans are much less and adherence to above limits, also in the case od DC fields is nonetheless advisable.

Present research has not been able to link any causal link between these fields and any disease. The American Physical Society, in a national policy statement, that was reconfirmed on 15 April 2005, states:

"The scientific literature and the reports of reviews by other panels show no consistent, significant link between cancer and power line fields. This literature includes epidemiological studies, research on biological systems, and analyses of theoretical interaction mechanisms. No plausible biophysical mechanisms for the systematic initiation or promotion of cancer by these power line fields have been identified. Furthermore, the preponderance of the epidemiological and biophysical/biological research findings have failed to substantiate those studies which have reported specific adverse health effects from exposure to such fields. While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant, and causal relationship before one can conclude that such effects do occur. From this standpoint, the conjectures relating cancer to power line fields have not been scientifically substantiated.

These unsubstantiated claims, however, have generated fears of power lines in some communities, leading to expensive mitigation efforts, and, in some cases, to lengthy and divisive court proceedings. The costs of mitigation and litigation relating to the power line cancer connection have risen into the billions of dollars and threaten to go much higher. The diversion of these resources to eliminate a threat which has no persuasive scientific basis is disturbing to us. More serious environmental problems are neglected for lack of funding and public attention, and the burden of cost placed on the American public is incommensurate with the risk, if any."
(http://www.aps.org/policy/statements/95_2.cfm)

Continuing research is giving particular emphasis to the effects of magnetic fields that are caused by high currents that are not associated with high voltage only. In the case of low voltage networks the current carrying conductors are closer to the affected persons.

2.7 Field Analysis Methods

Fields are nowadays often solved using numeric digital field simulation packages. The principal methods used are shown in Fig. 2.17.

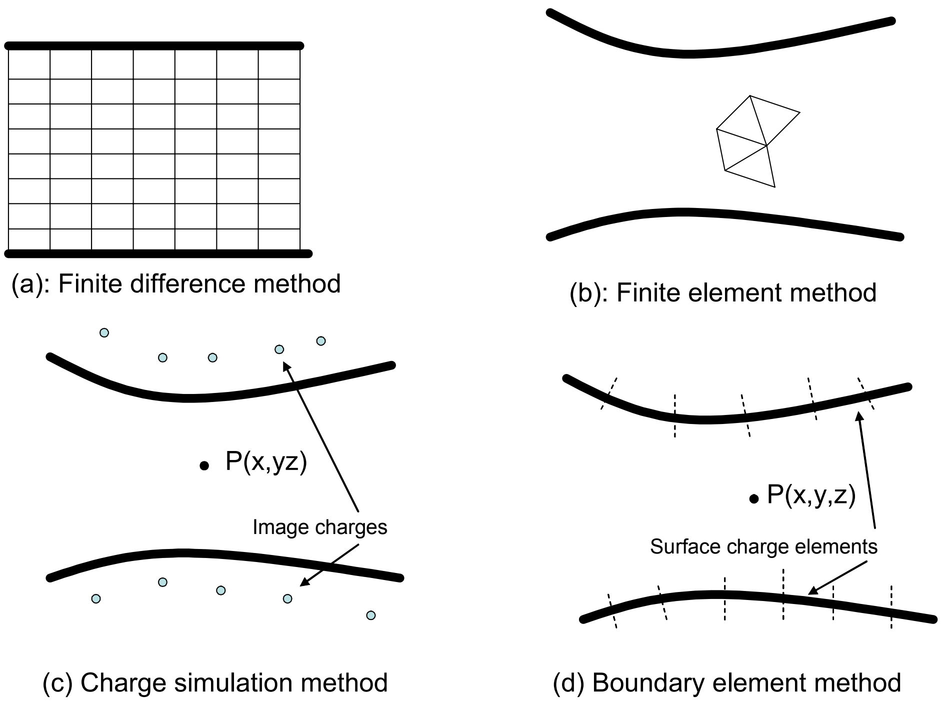


Fig. 2.17: Principal methods of field simulation

In the finite difference method (FDM) and the finite element method (FEM), the relevant field region is subdivided into a rectangular or triangular mesh, respectively. The potentials at the node points are solved numerically, taking into account the boundary conditions. In the case of the electrostatic field, this amounts to a numeric solution of La Place's equation for the region:

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=0 \qquad (2.24)$$

In the case of the charge simulation method (CSM), fictitious charges are placed inside the electrodes (outside the field region). For the boundary element method (BEM), surface charge elements are placed on the electrode surface. The values of these fictitious charges are computed, taking into account the boundary conditions. Thereafter, the fields can be computed for any point, such as P(x,y,z) within the field region.
The field simulations in Figs. 2.7 to 2.12 were done using a boundary element package.

2.8 Review Questions

1. Air at atmospheric pressure breaks down at a stress of approximately 3 kV/mm. Consider the following configurations and estimate the voltage where breakdown (or corona) starts:

- A uniform field gap of 100 mm *(300 kV)*
- Two co-axial cylinders: radius of outer cylinder 110 mm, inside cylinder radius 10 mm. *(71.94 kV)*
- Two concentric spheres: radius of outer sphere 110 mm, inside sphere radius 10 mm. *(27.27 kV)*

Discuss the results.

(5)

2. Air at atmospheric pressure breaks down at a stress of approximately 3 kV/mm. Consider the following configurations and estimate the voltage where breakdown (or corona) starts:
   - A 200 mm gap between two uniform field electrodes. *(600 kV)*
   - A 200 mm gap between two 20 mm radius parallel cylinders. *(261.6 kV)*
   - A 200 mm gap between two 20 mm radius spheres. *(109.1 kV)*

   Comment on the difference of the answers obtained.

(10)

3. (a) A spherical electrode is far from earthed objects. The maximum rms voltage on the sphere 500 kV . What are the requirements regarding sphere diameter to keep the maximum stress below 15 kV/cm (peak)? *(47.14 cm)*

(5)

(b) A spherical electrode has to be fitted to a 20 mm diameter rod as shown in Fig. 2.17 (top). Determine the diameter of the sphere if the electrodes are at 100 kV rms. Assume the distance to the laboratory walls to be 5 m. (Hint: regard the laboratory as an outer cylinder with a 5 m radius and ensure that the maximum stresses on the cylindrical and spherical sections are equal.)
(R_1= 62.15 mm)

(5)

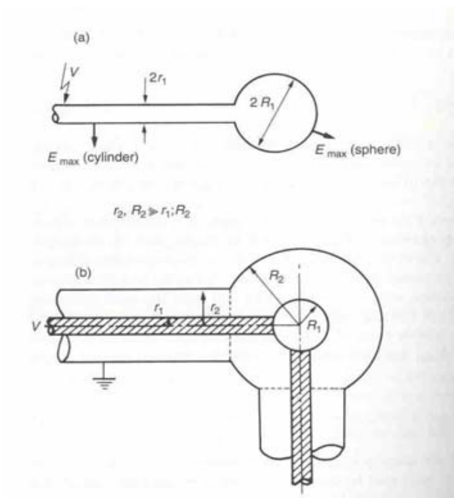


Fig. 2.17: Question 3

(c) In Fig. 2.17, r_1 = 30 mm. Determine the other dimensions by ensuring that the maximum field strengths in the cylindrical and spherical sections are equal. Determine the maximum working voltage of the system if the stress has to remain below 2 kV/mm. (Hint: Use the optimal r_2/r_1 – and R_2/R_1-ratios).
(r_2=81.54 mm, R_1= 60 mm, R_2= 120 mm, V= 60 kV)

3 HIGH VOLTAGE INSULATING MATERIALS

To Air: For being so forgiving …

Where a voltage difference exists between two conductors, it is necessary to keep them apart to prevent the undesirable flow of electrical current from the one conductor to the other. When the conductors are separated (*isolated* from each other) a layer of gas (air) fills the space between them, forming the electrical *insulation*[1]. As shown in chapter 2, the field strength in this gap will depend on the voltage difference and the gap size. In the present chapter it will be shown that, if the field strength in the gap exceeds a certain threshold, the gas in the gap will seize to act as an insulating material, but will become ionized and break down. Prior to flashover, corona discharges occur in regions of high field strength.

The most commonly used insulating gas is air at atmospheric pressure, as employed on overhead power lines and open air substations. In this type of application, a factor of major significance for the maintenance of equipment and for auto-reclosing systems is the ability of air to restore its insulating properties after disconnection of the voltage.

Certain gases are electronegative and discharges are suppressed by the de-ionizing action of the gases. The most important gas of this type is sulphur hexafluoride (SF_6) which is used at a higher pressure in compact metal clad gas-insulated substations (GIS).

It will also be shown that certain types of liquids can be used as insulating materials, having better insulating properties than gases. Likewise, solid insulating materials are potentially better insulating materials than liquids and gases. Unlike gases, liquid and solid insulating materials are generally not self-restoring. The properties and failure mechanisms of solid and liquid materials are discussed in this chapter.

3.1 Gases

The main insulating material used in outdoor power systems is air, consisting mainly of nitrogen and oxygen at ambient pressure and temperature. Compressed gases, such as

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[1] **insulate:** to separate by a non-conductor **(insulator**) of electricity – **isolate**: to disconnect (two or more sections of a network from one another by means of an **isolator or isolating switch**). In Germanic languages such as German or Afrikaans the equivalent of 'insulate' does not exist. (German: *isolieren (isolator)*, Afrikaans: *isoleer (isolator)* as translation of both **insulate (insulator)** and **isolate (isolator).**

SF_6, are used in indoor equipment. These gases are normally good insulators, i.e. they do not conduct electricity. A gas atom, like any atom, consists of a nucleus, having a positive electric charge and negatively charged electrons in the orbits. Normally, the gas atoms have zero charge as the positive and negative charges cancel out and unlike in the case of conductors of electricity, the electrons are not mobile. However, under certain conditions, notably a high electric field, the gases can become ionized as electrons are freed and cause the flow of electrical current. This is manifested as electrical discharges that develop in the high field regions, leading to sparks (low current discharges) or power arcs (high energy discharges). Lightning is an impressive manifestation of this effect.

3.1.1 Ionization

Collision ionization

The ionization process can be explained by considering the uniform field between electrodes, as shown in Fig. 3.1. The space between the plates is filled by gas atoms or molecules with free space between them. The process is initiated by the presence of free electrons in the atmosphere, due to ionization by cosmic radiation. Such an initial electron is accelerated in the field away from the negatively charged plate (the negatively charged electron is repelled by the negative electrode) and it may collide against an atom or molecule of the gas.

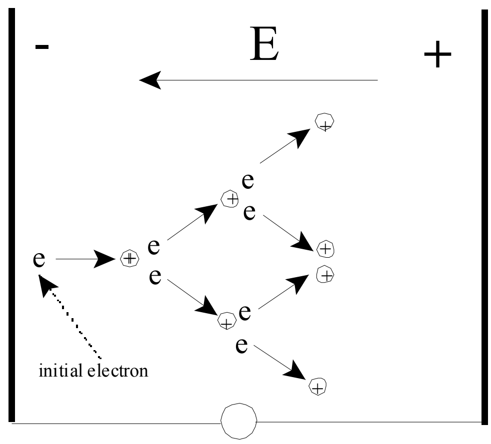

Fig. 3.1: Ionisation by electron collision with gas atoms

If the initial electron attains a high enough speed, it may, during an inelastic[2] collision, transfer some of its kinetic energy to the gas molecule. If this energy exceeds the ionization energy of the gas atom, one or more electrons may leave their orbits and the atom will lose a negative charge, thus becoming a positive ion.

The free electrons are accelerated towards the positive electrode and may, depending on the density of the atoms, partake in further collisions. As will be seen later, the probability of a collision depends on how densely the atoms are packed.
Apart from the collision mechanism, ionisation is also effected by the following processes:

[2] During an *elastic* collision, kinetic energy is conserved, but in an *inelastic* collision kinetic energy is converted to other forms of energy, such as heat and potential energy.

* *thermal ionization* due to heating;
* *photo ionization* due to photons, emitted when excited electrons return to their normal orbits.

Avalanche formation: Townsend's primary ionization coefficient

Townsend's first ionization coefficient (α) is defined as the number of ionizing collisions that take place during a unit length movement of one electron as explained in the previous section..

Based on this definition it is clear that during the movement of n electrons over a distance dx, dn new electrons are freed (also dn positive ions are formed), such that:

$$dn = n\,\alpha\,dx$$

$$\frac{dn}{dx} = \alpha\,n$$

Solution of this differential equation over the distance between the electrodes leads to

$$n = n_0 e^{\alpha x} \qquad (3.1)$$

where n_0 is the number of electrons at the cathode (negative electrode) and x the length of the discharge.

It is clear that the number of electrons and positive ions increases exponentially with x. Such a discharge is called an avalanche. A typical avalanche is shown in Figure 3.2. The mass of a hydrogen positive ion is 1860 that of an electron. It therefore accelerates much slower than the electrons. The fast moving (high mobility) electrons are at the tip of the avalanche with the heavy positive ions (low mobility) moving slowly towards the negative electrode.

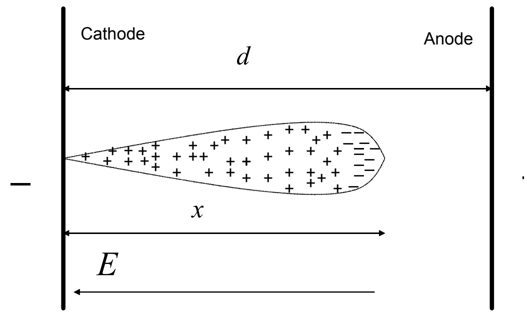

Fig. 3.2: An avalanche, consisting of fast moving electrons and slow positive ions

The discharges as described in this section are non-self-sustaining, i.e. they continuously require initiating electrons and as soon as the initiating electrons cease to appear, the process stops[3]. Such avalanches alone can not lead to flashover, but require a positive

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[3] This phenomenon is exploited in the Geiger counter, an instrument that is used to detect radioactive radiation. The radio-activity causes electrical ionization of the gas in the tube; the resulting current pulses are amplified and converted into an audible pulse.

feed-back process to develop into a flashover. Townsend showed that secondary processes, such as ion impact at the cathode or photo-ionization, provide such feed back. This will be discussed in section 3.1.3.

3.1.2 Electronegative gases, attachment and de-ionization

Certain gases have the property of electronegativity or electron affinity, whereby free electrons are attracted and become attached to the molecules of the gas. This is an important property, for, as was shown in the previous section, the number of free electrons plays a major part in the process of electron multiplication and avalanche formation. The attachment process is represented by the attachment coefficient, η, defined as the number of attachments that take place during a unit length movement of one electron.

Allowing for this attachment process, the counterpart of eq. (3.1) for electronegative gases becomes:

$$n = n_0 e^{(\alpha-\eta)x} \qquad (3.2)$$

The electron multiplication is obviously less than in eq. (3.1) that is valid for non-attaching gases. If $\eta > \alpha$, the exponent is negative and avalanche growth is terminated.

The most important gases from a power system point of view are oxygen (a 20% constituent of air) and sulphur hexafluoride. The SF_6 molecule has a regular octahedral structure and is about 5 times as heavy as air. The gas is colourless and non-toxic in its pure form but can cause suffocation due to its weight.

The following attachment processes occur in SF_6:

$$SF_6 + e \rightarrow SF_5 + F + 2e \qquad (3.3)$$

$$SF_6 + e \rightarrow SF_6^- \qquad (3.4)$$

$$SF_6 + e \rightarrow SF_5^- + F \qquad (3.5)$$

SF_6 gas is used extensively as an insulating medium in gas-insulated systems (GIS) (section 1.2.1) and also in circuit breakers (1.3.7).

3.1.3 Self-sustained gas discharges: Townsend discharges

As mentioned in section 3.1.1, this process continues, aided by other similar processes (photo ionization and cathode bombardment by the positive ions) until the conductivity of the gas becomes such that a discharge current flows and flashover occurs.

For example, as was shown in Fig. 3.2, positive ions are formed during the avalanche process. A single electron, starting at the cathode, produces $e^{\alpha d}$ -1 new electrons and positive ions while moving over the distance d towards the anode. The heavy ions experience a force due the electric field and are accelerated towards the cathode, as shown in Fig. 3.3. The cathode is a conductor and it can emit electrons when receiving sufficient external energy, either thermally, through photons or by impact. Over the distance to the cathode the heavy positive ions build up sufficient kinetic energy to release more initiating electrons during impact with the cathode. Each colliding electron releases γ new electrons, γ being Townsend's second ionization coefficient, which is defined as follows:

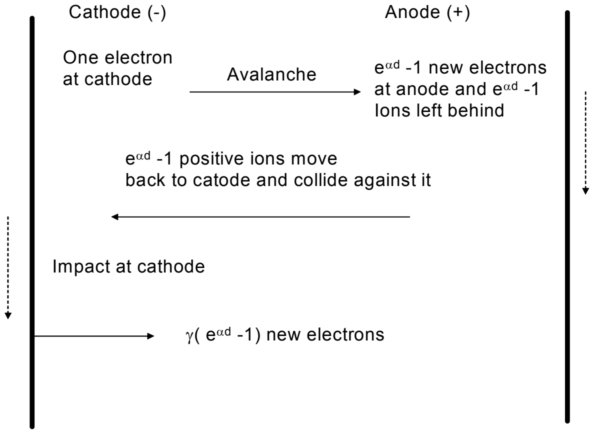


Fig. 3.3: Secondary ionization due to cathode collision

Townsend's second ionization coefficient (γ), is defined as the number of electrons released at the cathode by the impact of one positive ion.

Upon impact with the cathode, $\gamma(e^{\alpha d}$ -1) new electrons are released, as shown in Fig. 3.3. Clearly the population of electrons will grow, providing that

$$\gamma(e^{\alpha d} - 1) > 1\,. \tag{3.6}$$

$$e^{\alpha d} > 1/\gamma + 1$$

Thus at flashover: $\alpha\, d = \ln(1/\gamma + 1)$

For the normal range of values of γ, it has been found that the right hand side of this equation remains almost constant. Thus:

$$\alpha\, d > k \tag{3.7}$$

with k in the range 2.5 $\rightarrow$18. Note that, since $e^{\alpha d}$ is the number of ions in one avalanche, this range corresponds to avalanches of sizes 12 $\rightarrow$ 0.6x10^8 electrons).

The conditions where eq. (3.7) is satisfied, leading to flashover, are explored further in section 3.1.5.

3.1.4 Self-sustained gas discharges, streamer discharges

Raether, Loeb and Meek studied avalanche growth by means of Wilson cloud chambers during the breakdown of gaps for various pressures and gap lengths. They observed deviations from the Townsend theory (and Paschen's Law) in the case of longer gaps. They also showed that, if the length of the avalanche becomes large, the negative and positive charges in the avalanche distort the field to such an extent that new avalanches form ahead of the original avalanche, eventually bridging the gap. As is shown in Fig. 3.4, the fields, caused by the space charge, strengthen the applied field in the regions ahead and towards the tail of the original streamer. The ionization coefficient α is a function of the field strength (E) and it is therefore increased in these regions - to such an extent that new avalanches are triggered by photons that emerge from the original avalanche.

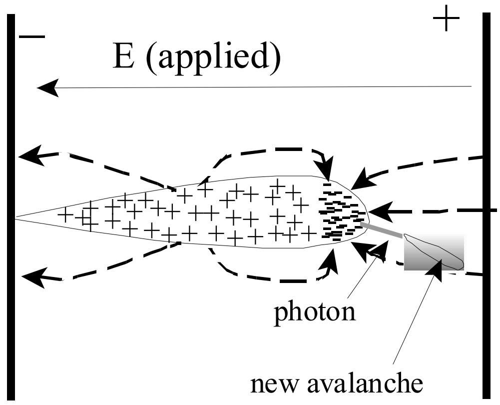


Fig. 3.4: Streamer Formation

The critical number of ions in an avalanche has been determined empirically to be of the order of 5.10^8, i.e. $\alpha x_c = 20$, with x_c the critical avalanche length.

Eventually, the conductivity of the gap increases to such an extent that flashover follows. For a non uniform field the following equation applies:

$$\int_0^x \alpha \, dx = 20 \qquad (3.8)$$

3.1.5 Flashover of uniform gaps: The effect of pressure and gap length (Paschen's Law)

In small uniform gaps it has been found empirically that, at standard pressure (1 bar = 101,3 kPa = 760 mm Hg) and temperature (20 °C), that breakdown occurs at a field strength of approximately 30 kV/ cm. In these gaps the Townsend flashover mechanism prevails.

At lower pressures the gas molecules are less densely packed and the mean free path between collisions is longer. The electrons therefore attain higher speeds before colliding

with the gas molecules, resulting in a lower flashover stress for the same gap. At very low pressures, such as used in vacuum contactors, the gas atoms are so far apart that the collision probability is low, with the result that ionisation and flashover takes place at a much higher value. The ionization coefficient α is an indication of the ionization probability of a gas and depends on the applied field strength E and the gas pressure p. This dependence can be shown to be the following:

$$\frac{\alpha(E)}{p} = A\exp(-Bp/E) \qquad (3.9)$$

where A and B are constants, unique for each gas.

Combining this equation with eq. (3.7) gives:

$$\alpha d = Ap\exp(-Bp/E)\, d = k$$

Substituting $E = V/d$ into this equation:

$$\alpha d = Ap\exp(-Bpd/V)\, d = k$$

.This leads to:

$$V_c = B\frac{pd}{\ln(pdA/k)} \qquad (3.10)$$

An interesting feature of this equation is that p and d occur together in the form pd. This leads to the formulation of Paschen's Law:

Paschen's Law: The flashover voltage of a uniform field gap is a function of the product: gap length times gas pressure.

An empirical relationship has been suggested by Sohst and Schröder for uniform gaps with pd values between 10^{-2} and 5.10^{2} bar cm:

$$V_c = 6.72\sqrt{pd} + 24.36\,pd \qquad (3.11)$$

with V_c the flashover voltage in kV (peak) and pd in bar cm.

Another, more simplified empirical formula for the critical stress E_a in kV/cm is that due to Townsend, with d the gap length in cm:

$$E_a = 30 + 1.35/d \qquad (3.12)$$

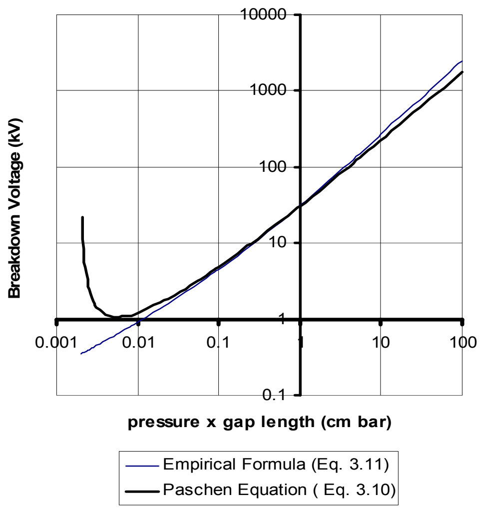


Fig. 3.5: The Paschen curve for air

Paschen's Law (eq. 3.19 with A = 6450 (bar cm)$^{-1}$, B = 190 kV/ (bar mm) and k = 13.3) and the empirical equation (eq. 3.11) are shown in Fig. 3.5. It will be noted that the Paschen curve shows a minimum at a specific pd-value, below which the breakdown voltage increases again. Typically, for air this minimum value is 352 V. This region corresponds to pressures well below normal atmospheric pressures, i.e. vacuum. The high flashover voltages obtained under vacuum is exploited in high voltage equipment such as vacuum circuit breakers, where pressures of the order of 10^{-7} mm Hg are used. In practical vacuum insulating systems, surface irregularities on the electrode surfaces have a marked effect on the flashover voltage.

The pressure dependence of the flashover process can be visualised with reference to Figure 3.6, wherein three cases are considered. The same gap is shown with different gas pressures: low medium and high. The gas molecules are shown schematically as spheres. Clearly the collision probability is low in Figure 3.6 (a) due to the low gas pressure. On the other hand, when the pressure is high, as in Figure 3.6 (b), the intermolecular distances are so short that the electrons cannot attain sufficient kinetic energy to cause ionization. In Figure 3.6(c) the intermolecular distances are optimal to allow a sufficient number of collisions and an adequate mean free path length between collisions.

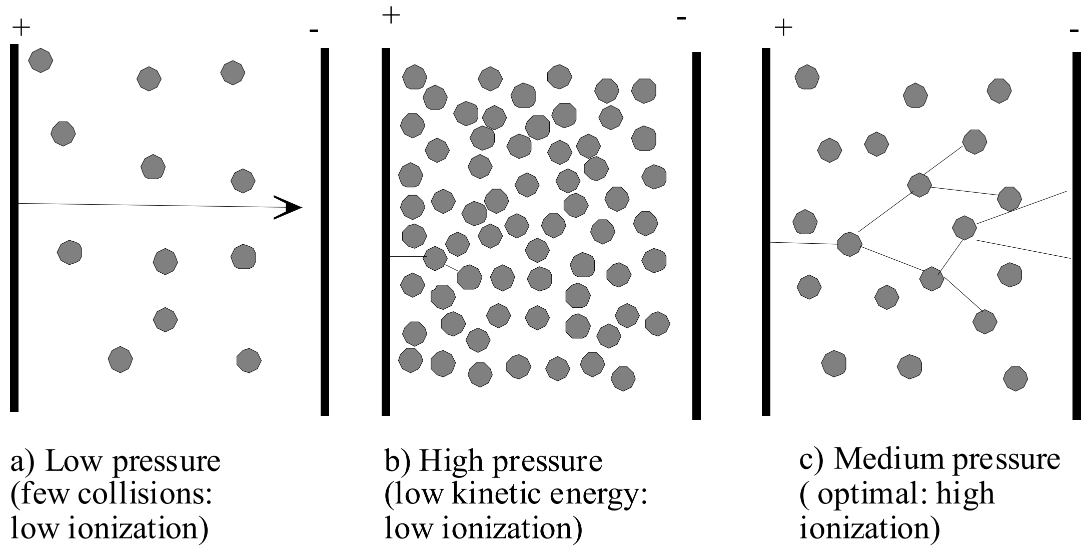


Fig. 3.6: Ionisation by electron collision with gas atoms

Example 3.1:

What is the flashover voltage of a uniform gap (Rogowski profile), with a gap of 1 cm and an air pressure of 1.013 bar? Use A = 645 (bar mm)$^{-1}$, B = 19.0 kV/ (bar mm) and k= 13.3 in eq. 3.10.

Solution:

$V = Bpd/ \ln(Apd/k) = (19 * 1.013 * 10)/\ln(645*1.013*10/13.3) = 31.06$ kV.

Example 3.2:

The empirical relationship of eq. 3.11 shows that the flashover voltage for a 1 cm gap near the coast (p = 1 bar) is 31 kV, while in Johannesburg (p = 0.8 bar) the flashover voltage is only 24.5 kV, a reduction of more than 20 %. Check the accuracy of this statement.

It is clear that altitude has a strong influence on the performance of gaseous HV insulation. Solid and liquid insulating materials are not directly affected by ambient pressure. Although the derivation of the Paschen relationship of eq. 3.10 pre-supposes a uniform field and the Townsend mechanism, it can be shown that a similar effect occurs in the case of the streamer and leader (see section 3.1.7) discharges. Measurements in the high voltage laboratory have to be corrected and referred to sea level.

3.1.6 Flashover of non-uniform gaps: the polarity effect

If the voltage across a non-uniform field gap is increased, avalanche activity occurs in the regions where the field is high (see *corona* in section 3.1.9). If the voltage is increased beyond the corona inception level, some avalanches develop into streamer discharges, bridging the gap to cause a complete flashover. The flashover voltage of a non-uniform gap is therefore much lower than that of a uniform gap of the same size. The "rule of thumb" of 30 kV/ cm therefore does not apply to non-uniform gaps.

Tests with DC and unidirectional impulses show that in a non-uniform gap, the lowest flashover voltage is obtained when the "sharpest" electrode has a positive polarity with respect to the other one. With AC, flashover therefore invariably takes place near the peak of the positive half cycle.

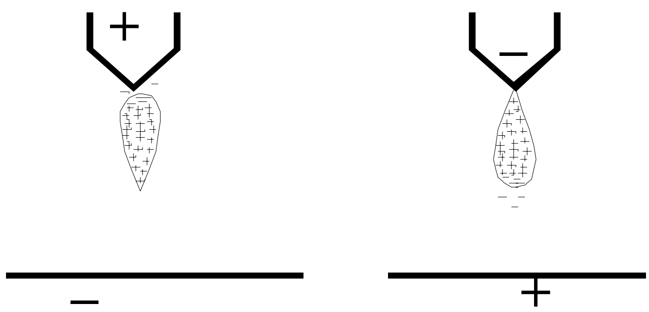


Fig. 3.7: Explanation of the polarity effect of DC flashover of an unsymmetrical arc gap.

This polarity effect can be explained by referring to Figure 3.7 where a positive and a negative sharp electrode are shown opposite a plane. In both cases the avalanches form in the region with the highest field strength (near the sharp electrode). In both cases the electrons with a low mass are swept away by the field and are absorbed by the positive

electrode. The heavier positive ions move away more slowly and positive space charge builds up near the sharp electrode.

In the case of the positive sharp electrode, the positive charge may be seen as an extension of the positive electrode, thus reducing the gap and increasing the field in the remainder of the gap. The ionization processes are therefore accelerated and flashover occurs.

Exactly the opposite applies in the case of the negative sharp point, as the space charge has a polarity (positive) that is different from that of the electrode. The field is thus reduced in the rest of the gap, and a higher voltage is required to cause flashover.

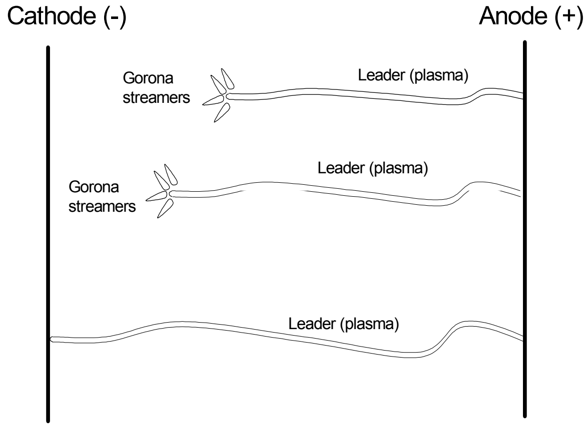


Fig. 3.8: Development of a leader discharge

3.1.7 Flashover mechanism of long gaps: Leader mechanism

For long air gaps, such as those encountered in EHV power systems, a different flashover mechanism applies, notably in the case of switching impulse voltages. Corona streamers form initially, but they merge into a thermally ionized column, called a leader. Long gaps (> 1 m) are particularly vulnerable to switching impulses as they allow flashover to develop in accordance with the leader mechanism. The mechanism has features that are similar to lightning development.

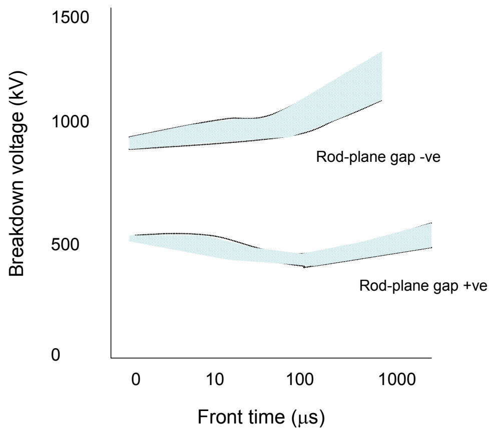


Fig. 3.9: Impulse flashover voltage as a function of front time.

The fact that the leader mechanism prevails for gaps larger than 1 m has important consequences for transmission system insulation. Fig. 3.9 shows impulse test results for a 1 m gap with varying front times. It will be noted that at a front time of the order of 100 μs, a minimum flashover voltage is obtained in the case of the positive rod-plane gap. This front time is of the same order as for switching impulses, and one can conclude that these gaps are vulnerable for positive switching impulses.

3.1.8 Flashover, sparks and arcs

Consider the schematic presentation of a section of a power system, shown in Fig. 3.10. The gap shown typically represents the shortest distance from the high voltage wire to ground – often across an insulator. Due to an overvoltage the air in the gap breaks down (flashes over) due to the increased electric field strength. The mechanism of flashover depends on the nature of the gap as indicated in Table 3.1. The wave shape of the overvoltage also affects the value of the breakdown voltage. Typically the flashover voltages of short duration impulses are higher than for AC and DC.

Often the flashover of the gap is initiated by an external overvoltage, such as a lightning surge. Once the gap has flashed over an arc is formed (provided that the impedance Z is not too high), maintained by the system voltage (AC or DC) and a large fault current flows that has to be cleared by the circuit breaker (CB in Fig. 3.10). If the impedance is high, it may not be possible for a stable arc to form; in such cases intermittent or repetitive *sparking* may occur.

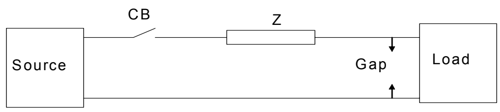


Fig. 3.10: Section of a power system with gap

Table 3.1: Occurrence of the different flashover mechanisms

Townsend mechanism	Streamer mechanism	Leader mechanism
➢ Small uniform gaps at atmospheric pressure. ➢ Larger gaps at low pressure (discharge tubes). ➢ < 5 bar mm ➢ AC and DC	➢ Medium sized uniform gaps. ➢ Medium sized non-uniform gaps. ➢ > 5 bar mm ➢ AC, DC and lightning impulses	➢ Large gaps on power systems. ➢ Gaps > 1 m, ➢ Switching impulses and AC.

The transition to an arc can be explained with reference to Fig. 3.11, showing the DC voltage/current characteristic a gas-filled gap. Although this illustration is strictly only valid for DC discharges in gas discharge tubes, similar phenomena occur in the case of AC air flashover. Initially, electron avalanches lead to Townsend discharges, until the sparking potential V_C is reached. At this point, glow corona sets in and the glow discharge changes into an arc. Fig 3.11 shows an important

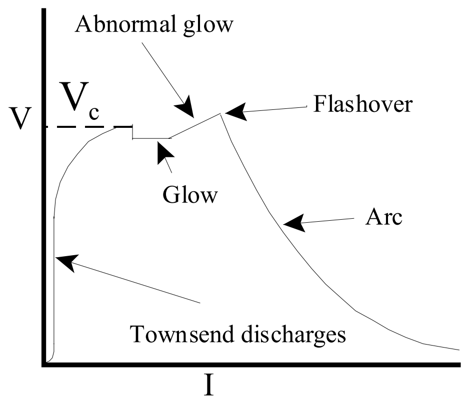


Fig. 3.11: The V-I curve, pertaining to corona and arc transition.

feature of arcs: the non-linear "negative resistance" characteristic, i.e. the arc voltage decreases with increase in current.

As explained in chapter 1, arcs also form when the contacts of a circuit breaker move apart. The circuit breaker's main function is to interrupt the arc and current.

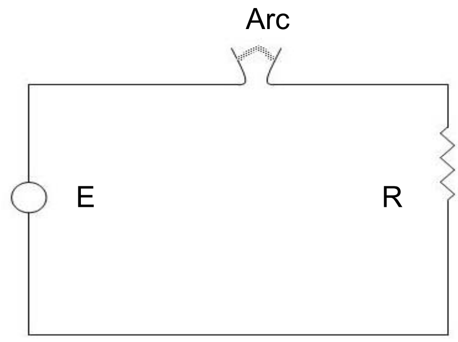


Fig. 3.12: Circuit for interruption of an arc.

Consider the problem of interrupting a DC current by a circuit breaker, as shown in Figure 3.12. In Figure 3.13 the nonlinear arc characteristics of arcs of increasing length are shown, together with the load line, representing the voltage source, E, and the load resistance, R. The stable operating points are also shown for each length of arc. It is clear that if the arc length exceeds a certain critical length, no stable operating point exists. In a DC circuit breaker the arc is elongated by:

- moving the circuit breaker contacts apart
- allowing the arc to move to the region where the contacts are further apart (arcing horns). This movement is facilitated by magnetic blow-out coils or by the thermal effect. The circuit usually also contains some inductance that complicates the current interruption process.

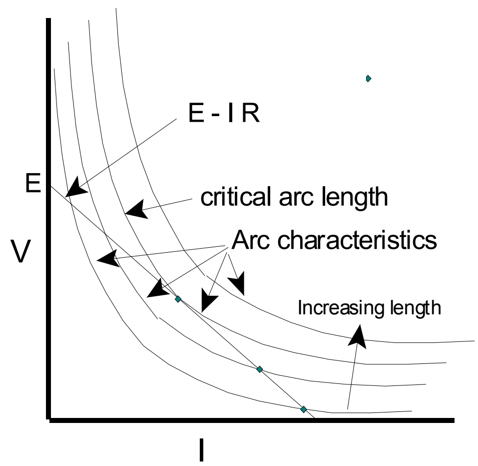


Fig. 3.13: Load line of circuit and arcs of increasing length.

3.1.9 Corona discharges

In the case of a non uniform gap the maximum field strength will occur near electrodes of small radius of curvature. The ionization threshold is therefore exceeded only in these areas. Partial discharges or corona therefore occurs in these areas. Corona is a self-sustaining discharge, occurring in the parts of the gap where the critical field strength is exceeded. If the voltage is further increased, final flashover develops from the corona.

Apart from being a pre-cursor of flashover, corona is also undesirable on the power system due to the electromagnetic interference caused, the additional corona losses and

the material (insulation) degradation due to the ultra violet radiation, emanating from the corona.

Corona on cylindrical conductors

In order to explain the phenomenon, a concentric cylindrical system is considered as shown is in Fig. 3.14. The radius of the inner conductor is 2 cm, the outer radius is 12 cm and the voltage between the electrodes is 150 kV. The distance between the two electrodes is therefore 10 cm, resulting in an average electric field strength of:

E = 150 / 10 = 15 kV/cm

For the graph in Fig. 3.14, the field strength has been calculated using eq. (2.2):

$$E_a = \frac{V}{a\ln(b/a)} \qquad (2.2)$$

Note that the field strength exceeds 30 kV/cm in the shaded region. In this region the air will in fact become ionised and will break down in accordance with the processes previously described, while the gas in the rest of the gap is not ionized. The surface field strength at the inception of stable visual corona is thus higher than 30 kV/cm.

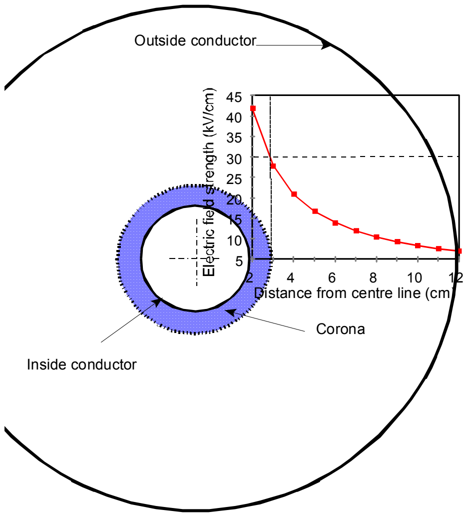


Fig. 3.14: Coaxial cylinders (12 cm/ 2 cm radii) at 150 kV- E > 30 kV/cm in shaded region.

Peek's formula is regarded as an empirical formula, but Cobine has shown that a simplified form can be derived, based on the Townsend criterion (eq. 3.12), which leads to Paschen's law.

He used Townsend's empirical form thereof:

$E_c = 30 + 1.35/d$ (kV/cm)

where $d = r_c - a$ is the gap length in cm.

For a cylindrical arrangement:

$$\frac{E_0}{E_c} = \frac{a}{r_c}$$

Using these constraints he arrived at the following equation:

$$E_a = 30(1 + 0.3/\sqrt{a}) \text{ kV(peak)/ cm} \qquad (3.15)$$

The general form of Peek's equation is:

For coaxial cylinders:

$$E_a = E_0 m\delta(1 + K\ (\delta a)^{-s})$$ (3.16)

with m: surface factor (0<*m*=<1)

E_0, K and s: constants

and $\delta = \dfrac{p(t_0 + 273)}{p_0(t + 273)}$ (3.17)

with p: atmospheric pressure

p_0: standard pressure (1 bar)

t: temperature

t_0: standard temperature (20°C)

Various researchers have assigned different values to these constants. These constants are given in Table 3.2.

Table 3.2: Constants in Peek's equation for coaxial cylinders

	E_0	K	s
Peek (AC): coaxial cylinders	31	0.308	0.5
Peek (AC); parallel wires	30	0.301	0.5
Heymann	24	0.104	0.42
Whitehead (DC+)	33.7	0.24	0.5
Whitehead (DC-)	31	0.308	0.5

Example 3.3:

Calculate the rms voltage (the visual critical corona voltage), corresponding to Ea, to be applied to a concentric cylindrical arrangement with a 5 mm radius (a) for the inner conductor and a 200 mm radius for the outer cylinder (b). Use δ = 1 and m = 1.

Solution:

From eq. (2): $V = E_a\, a\, ln(b/a)$,

$V = 31m\delta(1+0.308/\sqrt{(\delta\, 0.5)})\ 0.5\ ln\ (20/0.5)$

$= 3*1*1*(1+0.308/\sqrt{(0.5)})\ 0.5\ ln(40)$

$= 82$ *kV peak, i.e. 58 kV rms.*

Exercise 3.4:

Construct a graph of V as a function of conductor radii, ranging from 1 mm to 10 mm. Repeat the problem for Johannesburg, i.e. δ = 0.8.

AC Corona

The nature of AC corona current (at a voltage well above the inception level) is shown in Fig. 3.15. The current shown is the current supplied by the AC source. Initially, the current is purely capacitive (leading the voltage by 90 degrees). However, at corona inception, high frequency pulses appear, coinciding with the voltage peaks. Eventually, low frequency continuous corona current pulses appear at the voltage peaks. Corona first starts in the negative half cycle as high frequency current pulses. Pulses caused by streamer discharges occur in the positive half cycle. These phenomena are summarised in Table 3.3.

Table 3.3: Corona pulse characteristics

Polarity	Phenomenon	Typical characteristics
Negative	Trichel pulses	Regular. 10 ns rise time
Positive	Positive Streamers	Irregular, 100 ns rise time

Images obtained using a UV sensitive video camera (Corocam Mark I) are shown in Fig. 3.16, together with the relevant electric field strength for the case of an Acacia conductor. A notable feature is the difference between the results of the different forms of tenderization. The severity of positive DC streamers is also noteworthy. Although most of the AC corona activity takes place during the positive half cycle, the difference between the AC and the positive DC images are clear.

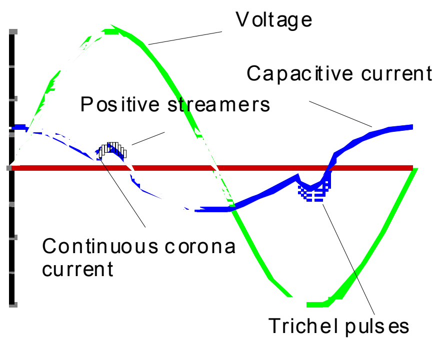


Fig. 3.15: AC Corona voltage and current wave forms

Corona at sharp points

A sharp point can be modelled as a small sphere (radius a). If the earthed objects are far removed from the energised sphere, the electric field at the sphere is mainly determined by the voltage and the sphere radius ($E_a = V/a$, eq. (2.3)). The corona inception gradient is also field dependant.

Problems caused by corona

Corona can be noticed as a bluish luminous discharge on conductors and ozone is formed.

- Interference (Radio Interference Voltage, RIV): The rapidly varying corona current pulses, especially the positive streamer discharges, shown in Figure 3.15, radiate electromagnetic interference in the range 0.2 to 10 MHz.

- Losses: The continuous corona current, shown in Figure 3.16, has a 50 Hz component that causes a power loss on the line. Normally, a well designed transmission line will have a low amount of radio-interference (RI) and therefore also small losses. During rain, however, corona forms on droplets on the conductor and both RI and power losses occur. Under such conditions, losses of tens of MW can occur on a 500 kV line.

There are also a number of empirical formulae for the fair weather loss available in the literature.

Measures to curb Corona

It is clear that corona is caused by the field intensification at sharp points, having a small radius of curvature. Sharp edges and points due to poor workmanship on high voltage hardware must therefore be avoided. Lines are normally designed to limit the surface gradient to low values. For EHV lines it is necessary to use bundled conductors, i.e. each phase consists of a number of parallel conductors as explained in section 2.2.3. On the 800 kV lines 6 conductors are used. The six conductors are equivalent to one conductor with a large radius and the surface gradient and losses are therefore low. Likewise, a corona ring can be fitted to shield stress concentrations as is shown in figure 2.8.

Useful applications of Corona

Besides the nuisance value on the power system, corona has many useful applications, including: photocopying machines, electrostatic dust precipitators and ozone generators.

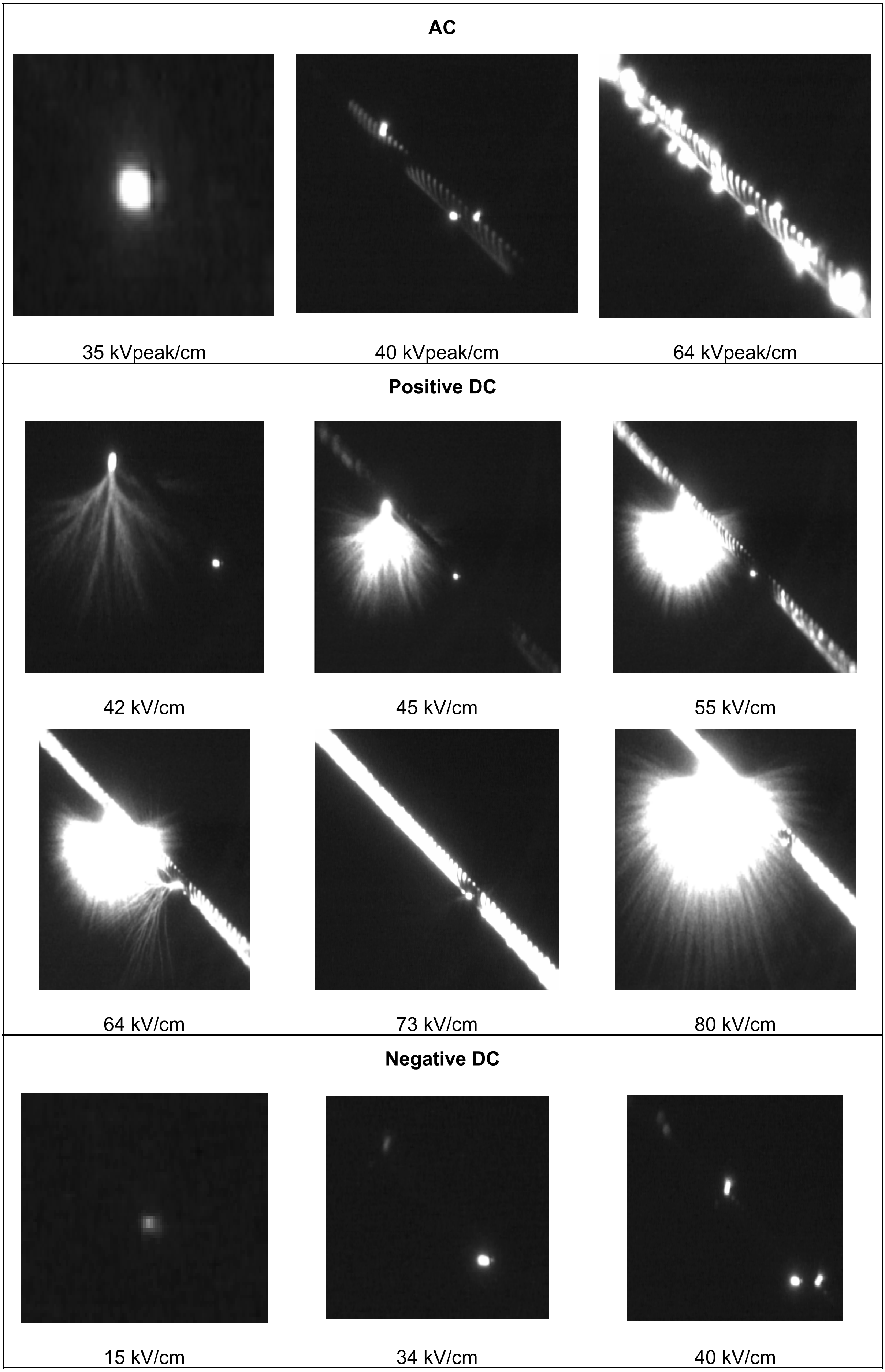


Fig. 3.16: Corona on a 6/1 stranded Acacia conductor (outside diameter 6.22 mm)

3.2 Solid and Liquid Insulating Materials

In the previous section the breakdown mechanisms of gaseous insulation media were investigated. It appeared that breakdown is often initiated by ionization caused by electron collision with neutral gas atoms. It was shown that, according to Paschen's law, the flashover performance improves as the gas density increases. It can therefore logically be expected that the electrical performance of liquids and solids will be better than that of gases. In practice, the electric strength of liquid and solid materials are however less than predicted due to impurities and imperfections.

Liquid and solid materials also classed as dielectrics, i.e. they have the property of polarisation, resulting in a dielectric constant that is higher than unity.

3.2.1 Dielectric constant (ε)

As shown diagrammatically in Fig. 3.17, the dielectric consists of dipoles. The dipoles could be due to the positive and negative charge centres of the molecules not coinciding or could be due to the charge distribution in the crystal structure of the material. When not energised, the dipoles are randomly arranged, as shown diagrammatically in Fig. 3.17(a). At the application of a voltage between the electrodes an electric field is established that acts on the dipoles to align them as shown in Fig. 3.17(b).

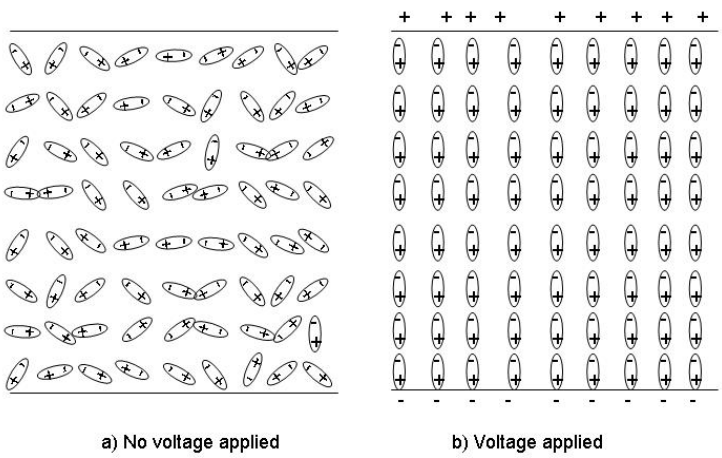


Fig. 3.17: Polarisation of a dielectric.

The effect of the dipoles is to bind additional charge on the electrodes, compared to the case where there is air between the electrodes, resulting in a higher capacitance ($C=V/Q$). The dielectric constant or relative permittivity (ε_r) can be defined as the ratio of the dielectric capacitance to the air capacitance:

$$\varepsilon_r = C_{diel} / C_{air} \tag{3.18}$$

Dielectrics with high dielectric constants are used in the manufacturing of capacitors. These dielectrics must also have a high electric strength, i.e. a puncturing strength.

3.2.2 Losses in dielectrics (tan δ)

Consider a capacitor formed by insertion of a slab of insulating material between two electrodes with a voltage V applied across the electrodes. The dielectric consists of dipoles on a molecular level. If the voltage is DC the dipoles (that are randomly oriented when not energised) align themselves as explained above in Fig. 3.17.

In the case of an alternating voltage, the dipoles vibrate in accordance with the frequency of polarity reversals, resulting in heating of the dielectric due to the friction (these dielectric losses are also the principle of operation of microwave ovens.)

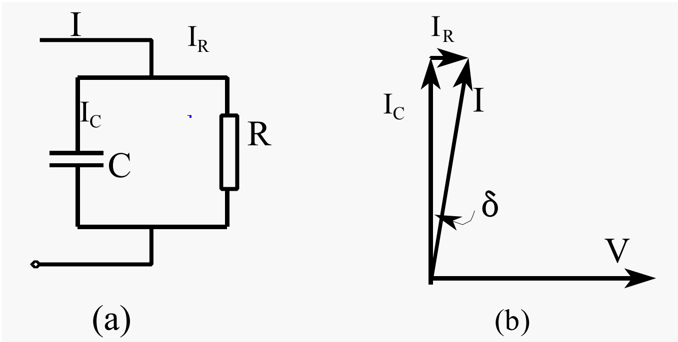


Fig. 3.18: Equivalent circuit and equivalent circuit for a practical capacitor

As no insulating material is a perfect insulator, there are also conduction losses. The equivalent circuit of a practical capacitor is therefore an ideal capacitor in parallel with a resistor as shown in Fig. 3.18(a). The corresponding phasor diagram is shown in Fig. 3.18 (b). For an ideal capacitor the angle between the current and voltage is 90 degrees. However, due to the resistive current component (I_R), the angle for a practical capacitor is 90 - δ.

The power loss in the capacitor is

$$P = VI_R = VI_C \tan\delta = V(2\pi fCV)\tan\delta = 2\pi fCV^2 \tan\delta \qquad (3.19)$$

The term tan δ is known as the loss factor and is clearly an indication of the quality of the insulating material and is also of importance for insulating liquids, such as transformer oil. It is measured with a Schering bridge.

From Fig. 3.18 also follows:

$$\tan\delta = \frac{I_R}{I_C} = \omega C_S R_S \qquad (3.20)$$

3.2.3 Typical solid insulating materials

As the intermolecular distances in solid materials are shorter than in liquids, a better breakdown performance is expected, from an avalanche formation perspective. The breakdown phenomena are also still not well understood as a various processes are

possible. Practical aspects, such as impurities and voids however detract from the theoretically expected performance.

There are a large number of different solids that have been employed as electrical insulation. Each material has limitations and strong points. Some of the main types are given in Table 3.4.

Table 3.4: Some typical solid insulation materials

Material	**Dielectric constant (typical)**	**tan δ (typical)**	**Typical Electric strength (kV/mm)**	**Properties**	**Applications**
Mica	5.5 - 7	$30. 10^{-4}$	-	Stable at high temperatures	Insulation of rotating machine windings (up to 20 kV) together with epoxies.
Paper	-	$20 – 50. 10^{-4}$	-	-	Oil-impregnated in HV transformer winding insulation.
Glass	4.5 - 7	$10 - 100. 10^{-4}$	10 -50	Brittle	Glass cap and pin insulators. Glass fibres together with epoxy resin
Porcelain	6	$3 – 30. 10^{-4}$	20 - 40	-	Insulators, bushings
Polythene	2.3	$1 - 10. 10^{-4}$	30 - 40	-	Cross-linked (XLPE) polythene used in hv cables up to 110 kV
PVC	5.5	$>100. 10^{-4}$	11 - 30	-	LV cables
PTFE	2	$2. 10^{-4}$	19	-	High temperature applications.
Epoxy resin, with silica filler	4	-	18	-	Encapsulation of MV Ct’s and VT’s Transformer bushings and insulators: cycloaliphatic resin
EPDM rubber	2 - 3	-	-	-	Insulators, using a fibreglass core
Silicone rubber	3 - 6	-	-	Hydrophobic surface properties	Insulators, using a fibreglass core

3.2.4 Failure mechanisms of solid insulating materials

The electric strength of solid materials are, as in the case of liquid insulating materials, much lower than the intrinsic strength predicted by physical considerations. The main practical failure mechanisms are: thermal breakdown, treeing caused by internal partial discharges and tracking caused by external arcing. The last two mentioned mechanisms are due to the interaction of different insulation materials and will also be dealt with in section 3.3, where mixed insulation systems are discussed.

a) Thermal breakdown

The dielectric and conduction losses of an insulating material increases non-linearly as a function of the temperature as shown in Fig. 3.19(a). These losses are also proportional to the square of the applied voltage (see eq. 3.19). Also shown in the figure is the heat

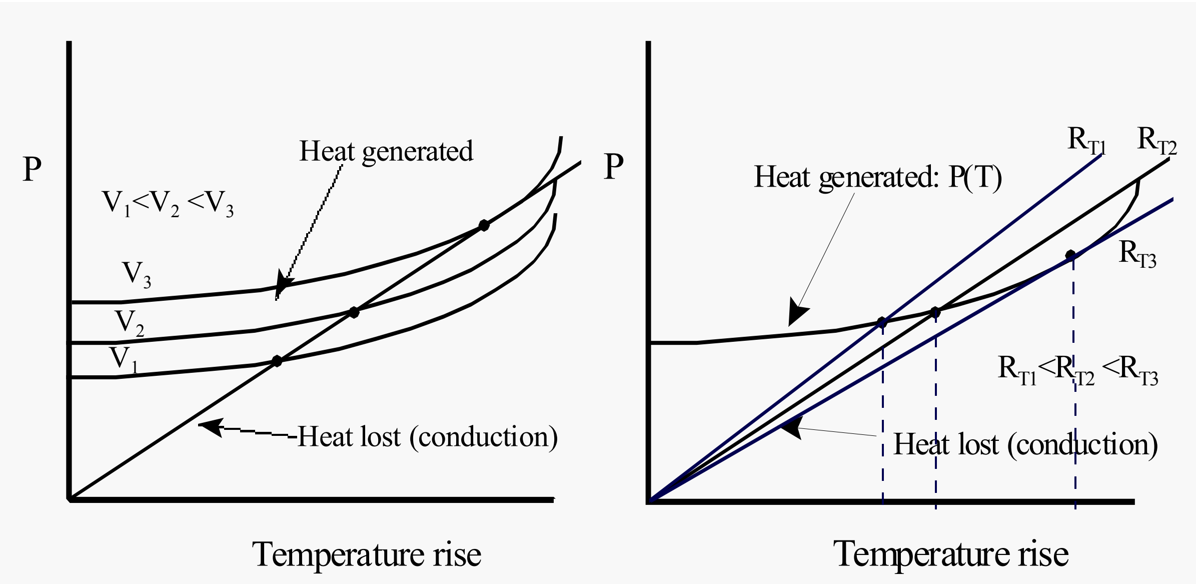


Fig. 3.19: Thermal runaway due to (a) voltage increase and (b) increase in soil thermal resistivity due to the drying out of the soil.

lost by the dielectric through conduction (Ohm's thermal law, refer back to section 2.4). The intersection indicated represents the operating point of the material. It is clear that at voltages higher than V_3, the heat generated exceeds the heat lost, resulting in thermal runaway.

This phenomenon may affect the performance of underground cables adversely. Consider the case of underground cables operating at a constant voltage, as shown in Fig. 3.19(b). Heating, due to dielectric losses and I^2-losses, causes the drying out of the surrounding soil. This increases the thermal resistance of the surrounding soil, thus causing thermal instability. It is therefore necessary to ensure that the thermal

conductivity of the surrounding ground is sufficiently high. The cables supplying Auckland in New Zealand failed recently under such circumstances due to overloading.

It is sometimes necessary to provide additional means of cooling, e.g. in a transformer.

b) Failure due to internal partial discharges

As was explained in section 2.2.4, electrical discharges may occur in voids in solid insulating materials due to the difference in dielectric constants of gases and solid materials. This aspect will also be discussed in more detail in section 3.3, where the performance of mixed insulating media is considered. These discharges may affect the lattice structure of the material and may lead to failure due to treeing.

Typical samples of treeing are shown in Fig. 3.20.

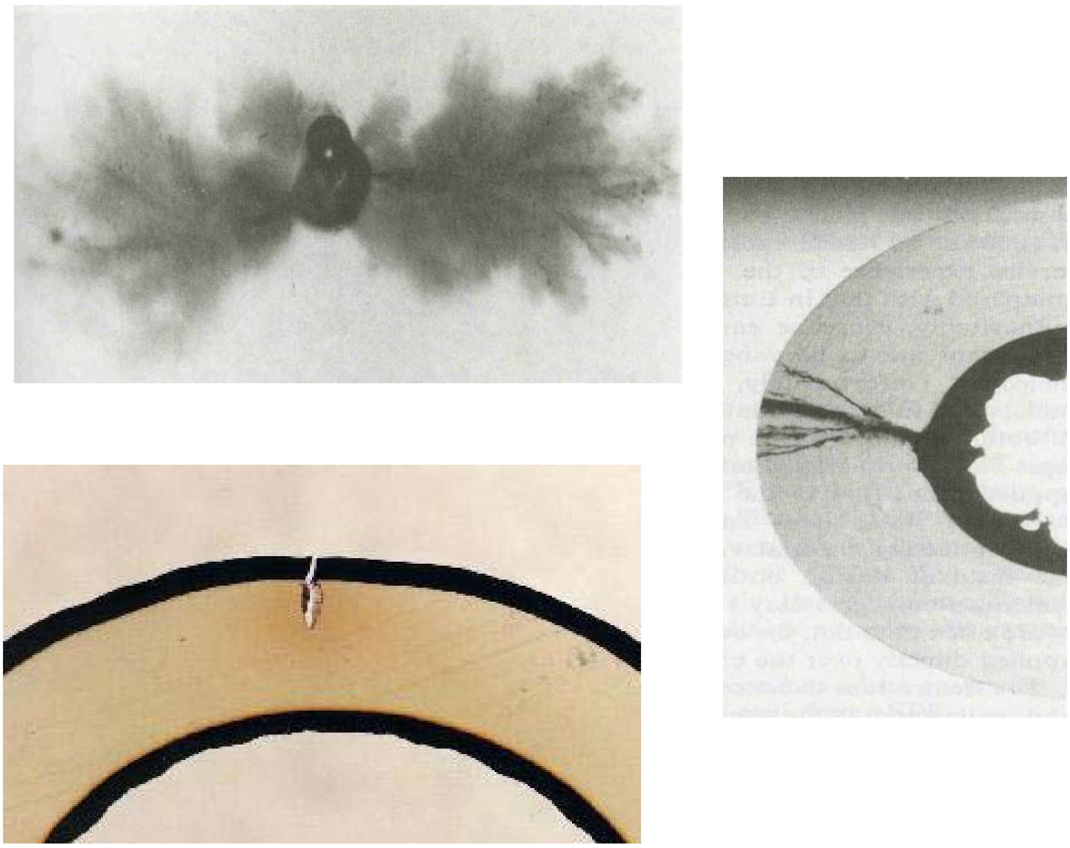


Fig. 3.20: Typical samples of treeing in solid insulation

c) Failure due to tracking and erosion

It will be shown in section 3.3.2(c) that, in poorly designed equipment, the electric field may be too high along the interface of the solid insulating material with the surrounding

air, resulting in the air at the interface breaking down and causing partial discharges on the surface of the dielectric. These discharges may attack the C-H bonds in certain polymers, resulting in the formation of conducting carbonaceous tracks on the surface of the dielectric. In materials that do not contain carbon, surface damage in the form of erosion is caused, without the formation of conducting tracks. These phenomena are often aggravated by the presence of dust, moisture and conductive pollution. Typical examples of tracking on a dielectric are shown in Fig. 3.21.

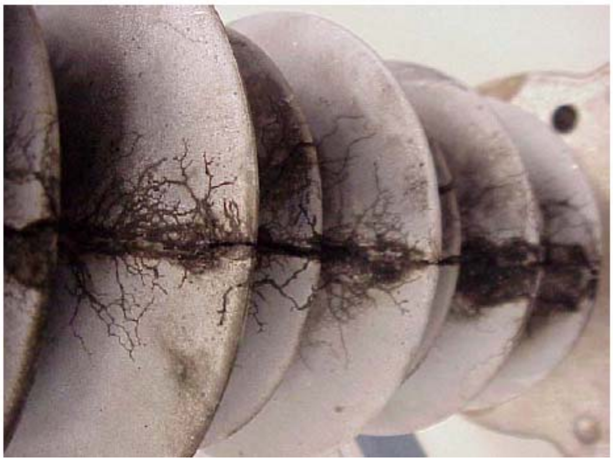


Fig. 3.21: Typical sample of tracking (and some erosion) on an outdoor insulator.

3.2.5 Liquid insulating materials

It appears from the previous section that solids have a superior electric strength compared to gases. However, gases and air in particular, have the property of being able to flow in or out of a specific region. This property is responsible for the ability of air gaps to recover after a flashover. Solid insulation on the other hand must be shaped or cast into position and allowed to set. Liquids, like gases, have the ability to penetrate into inaccessible positions and have a higher dielectric strength, compared to air at atmospheric pressure. However, the recovery of oil is less effective than that of air.

Insulating liquids usually are used in conjunction with solid insulation, e.g. paper in cables or transformers. The liquid impregnates the paper or linen insulating material and displaces air or gas.

The most common insulating liquid is mineral oil (transformer oil), derived from petroleum. It is used as an insulating material due to its chemical stability and economic considerations. In addition the heat absorbing properties are also used for the cooling of transformers.

3.2.6 Failure mechanisms of insulating liquids

The molecules in liquids are packed much more densely, compared to gases; thus higher breakdown strengths are expected for oils. The strength is however markedly affected by moisture and impurities in the oil.

- *Water content*

Water is absorbed either directly from the atmosphere or through condensation of water on the tank walls. Silica gel breathers are often used to keep the air above the oil in transformer tanks in a dry condition. Water, even in small quantities, causes a severe reduction in electric strength of oil. Typically, a water content of 50 parts per million causes the breakdown strength to drop from 50 to 23 kV/mm.

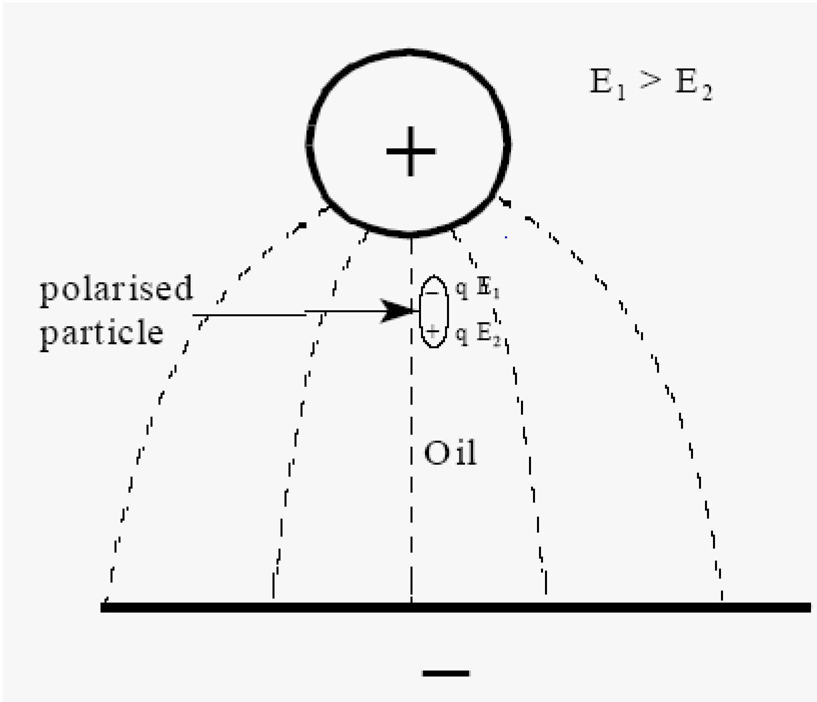


Fig. 3.22: The electrophoretic force on a dipolar particle in oil

Water may also be formed during the breakdown processes of the cellulose of the paper insulation of the transformer.

- *Impurities: Fibre bridges*

The presence of cellulose fibre particles affects the breakdown strength of the oil. Dipoles are induced on the particles and they consequently form chains to bridge the electrodes. As is shown in Fig. 3.22, the net force towards the positive electrode would be:

$$F = q(E_1 - E_2) \tag{3.21}$$

Due to the divergence of the non-uniform field, E_1 is larger than E_2, thus causing a net force towards the smallest electrode. This movement assists fibre bridge formation and breakdown. Water absorbed into the fibres aggravates the situation. The use of

insulating shields between the electrodes prevents the movement of the particles and also of fibre bridge formation.

- *Gas bubbles*

The presence of air or gas bubbles (often caused by discharges in equipment, such as transformers) in the oil initiate partial discharges (section 2.1.4) that can lead to breakdown of the oil.

- *Oil testing*

The standard oil test is a flashover test between two electrodes with a 2.5 mm gap. Oil for EHV transformers is required to withstand 60 kV.

Transformers are provided with a conservator, as shown in Figure 3.23, to allow the oil level to be above the connections to the bushings. As the oil heats up and cools down, air is sucked in via a breather. This breather is filled with silica gel to remove moisture from the oil.

Oil analysis (gas in oil) nowadays plays an important part in transformer diagnostics. Transformer insulation basically consists of oil and cellulose (paper). The main degradation processes of these materials are corona, pyrolysis (decomposition due to heating in the absence of oxygen) and arcing. Typical gases that are formed are: methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2).
The gases formed by the different phenomena are given in Table 3.5

Table 3.5: Gases formed during degradation processes [DiGiorgio]

Phenomenon	**Oil**	**Cellulose**
Corona	H_2	H_2, CO, CO_2
Pyrolysis (low temperature)	CH_4, C_2H_6	CO_2, (CO)
Pyrolysis (High temperature)	C_2H_4, H_2,(CH_4, C_2H_6)	CO, (CO_2)
Arcing	H_2, C_2H_2, (CH_4, C_2H_6, C_2H_4)	

The gases, trapped above the oil can be analysed, but analysis of the disolved gases in the oil (DGA) is proving to be the most useful method.

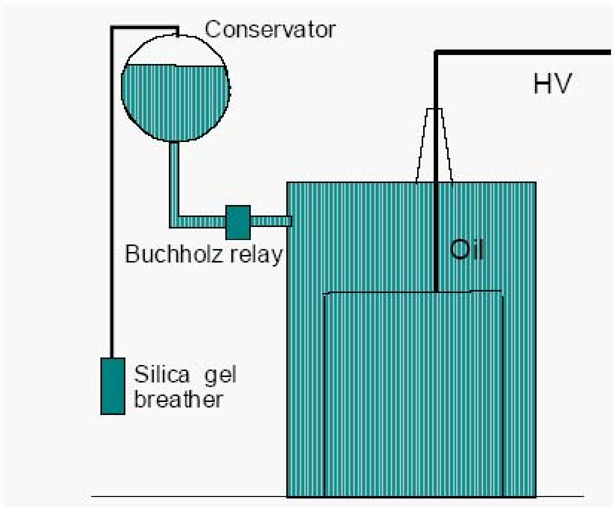


Fig. 3.23: Transformer with conservator and air breather

3.3 The Performance of Combinations of Gases, Solids and Liquids in Insulation Systems

In the previous sections the properties of gaseous, solid and liquid insulating materials have been investigated. Practical insulation systems, however, consist of a combination of these insulating materials. Often the combination is not by intentional design. A typical porcelain insulator is surrounded by air and the performance of the insulator will be affected by the properties of the air that is in parallel with the porcelain insulator. In actual fact, the air usually breaks down before the insulator can fail.

Another case of unintentional combination of insulating materials is the existence of unintentional voids in a solid insulation mass. During the manufacturing process of a cable or a cast epoxy resin current transformer, air or gas bubbles may form that find themselves in series with the main insulation. In section 2.2.4 it was shown that the field strength in the air bubble will be ε_r times as high as in the dielectric and, as indicated previously in section 3.2.4, discharges in these gas voids may lead to failure of the insulating systems due to treeing.

These principles are explained by means of examples in the following sections.

3.3.1 Parallel insulating materials

As indicated above, two parallel insulating systems do not affect one another – the weakest component will fail first.

Example:

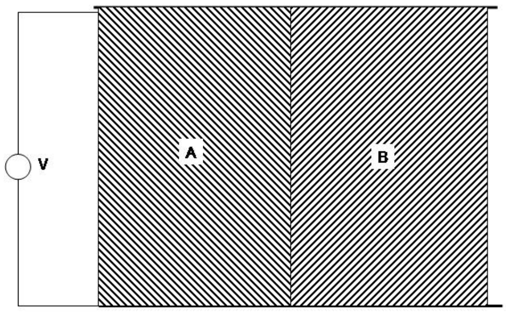


Fig. 3.24: Parallel Insulating materials

Consider the composite insulation system in Fig. 3.24. The two electrodes are d = 5 cm apart. Material A is a solid material with a relative permittivity of 6 and a dielectric strength of 600 kV/cm, while material B is an insulating oil with a 2.3 permittivity and a dielectric strength of 120 kV/cm. At what voltage will the system fail? Ignore end effects.

Solution:

The electric field strength in both sections is $E= V/d$. Note that the relative permittivities have no effect in the case of parallel systems. The failure voltage for the system is therefore:

$V=E\,d=$120*5 = 600 kV, i.e. the breakdown voltage of the weakest material.

It will be noted that in this case the field lines run parallel with the boundary between the two materials and that no one field line crosses both materials.

3.3.2 Series insulating materials

Often gaseous, solid and liquid insulating materials are intentionally used together in insulation systems. In other cases, air gaps or bubbles occur inadvertently in solid or liquid insulation systems.

a) Internal partial discharges:

The effect of field lines crossing two different insulating media is explained by way of an example.

The dielectric strength of solid and liquid insulating materials is in excess of that of gases (excluding SF_6 at high pressure). For that reason, oil is used in transformers and epoxy resin is used to encapsulate components such as 11 kV CT's. The following example will, however, show that the introduction of a solid material into a gap may in fact make matters worse if care is not taken to avoid air bubbles or gaps.

Example:

In Fig. 3.25 (a), a uniform air gap of 10 cm is shown with a voltage of V = 200 kV across the gap. It follows that E = 200/ 10 = 20 kV/cm. The gap will not flash over at this voltage.

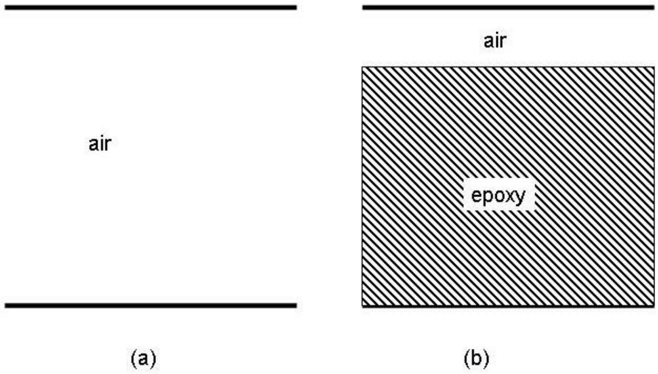


Fig. 3.25: Series dielectrics

In order to "improve" the reliability, a 9 cm thick sheet of epoxy with a relative permittivity (dielectric constant) ε_r = 3 was introduced in the gap as shown in Fig. 3.25 (b).

From eq. (2.15) follows that in Fig. 3.25 (b):

$E_{air} = \varepsilon E_{epoxy}$

Also:

$V = 200 = E_{air}\, 1 + E_{epoxy}\, 9 = E_{air}\, (1 + 9/\varepsilon_r) = E_{air}\, (1+9/3) = E_{air}\, 4$

Thus:

E_{air} = 200/4 = 50 kV/cm

The air in the "gap" thus breaks down, although the insulation does not fail. The continuous discharges and accompanying UV and ozone generation could however cause the insulation to deteriorate over a long time and eventually carbonisation, tracking and treeing may lead to failure.

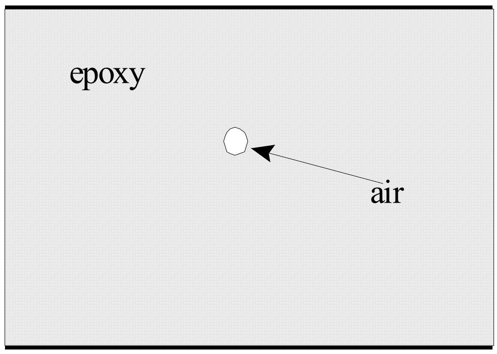


Fig. 3.26: Gas void in a solid dielectric.

The same phenomenon occurs where an air bubble is trapped in an epoxy casting, as shown in Fig. 3.26. The field strength in the bubble is, similar to the above case, higher than in the epoxy. The dielectric strength of the air, on the other hand, is less than that of the epoxy. Discharges therefore occur in the bubble and attack the crystal structure of the solid material, leading to treeing and possibly eventual failure.

Diagnostic test methods exist to detect these discharges in time to prevent failure. Epoxy impregnation and casting is performed under vacuum to remove air and gas bubbles. Polythene cables are also subject to this type of discharge when air voids exist in the insulation or at the interface of the conductor and insulation.

b) The design of components, consisting of different insulating media

Fig. 3.27 shows a typical power line insulator, energised at 20 kV. It will be noted that the equipotential lines are more closely spaced in the regions between the sheds, representing a higher field strength in those regions. If not properly designed, discharges can occur between the sheds.

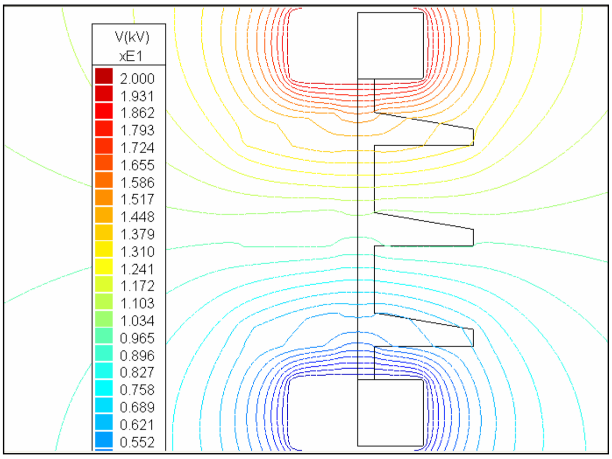


Fig. 3.27: Equipotential lines of an insulator

c) Surface discharges

Another form of partial discharge occurs along the surface of an insulating material. Consider the configuration of Fig. 3.28, showing a rod electrode, resting on a sheet of insulating material, such as glass. The set-up is typical for the determination of the dielectric (puncturing) strength of a solid insulation sample. The rod is energised with a high voltage. Line abc is a typical field line. Note that section ab lies in the air while bc traverses the dielectric. At the interface the relationship $\varepsilon_1 E_1 = \varepsilon_2 E_2$ indicates that the field strength in air will exceed that in the glass by the ratio of the permittivities. In addition, air has a lower dielectric strength compared to glass. The air on the surface of the insulating material therefore breaks down, resulting in streamer discharges, giving a sunflower-like pattern as shown in Fig. 3.29.

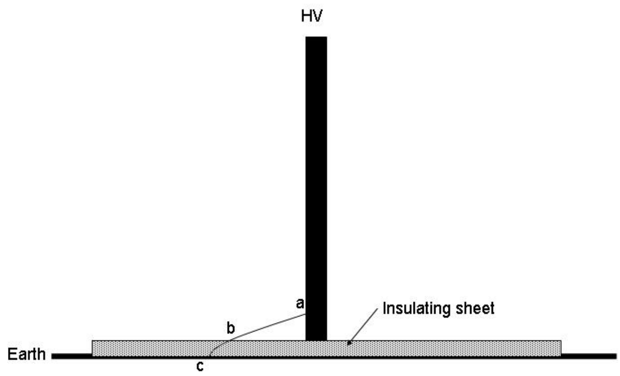


Fig. 3.28: Surface Discharge

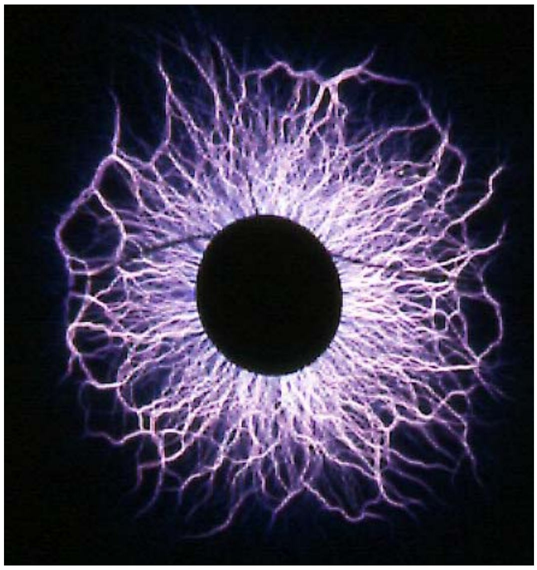


Fig. 3.29: Surface Discharge Streamers

These discharges also occur on other configurations where the field lines traverse air and a dielectric "in series", such as bushings and insulators. Prolonged discharges of this nature could cause:

- erosion of the material
- chemical degradation
- carbonisation along the surface, called tracking

Exercise:

Show how surface discharges can occur in the vicinity of an epoxy transformer bushing (Fig. 3.30).

3.4 Insulator pollution

In the case of insulator pollution the field pattern in the vicinity of the insulator is distorted by the presence of the conducting pollution layer on the insulator surface. A clean insulator string may be represented by a capacitive network as shown in Fig. 3.31. Each

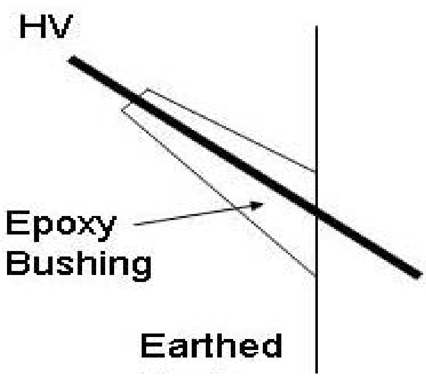


Fig. 3.30: Transformer Bushing

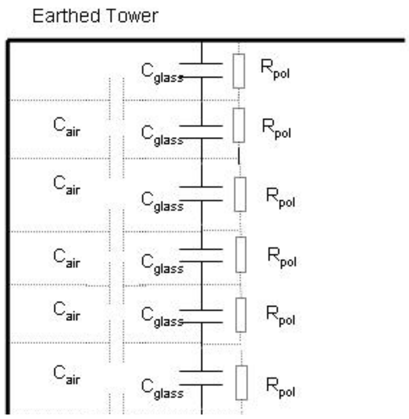


Fig. 3.31: Polluted Insulator String

glass disc is represented by a capacitor C_{glass}. The capacitances C_{air} represent the field lines through the air. Under clean conditions a predictable reasonably linear voltage division is obtained across the string.

Near the coast or in industrial areas the insulator surface becomes contaminated by a pollution layer that may become conductive during fog or light rain, represented by the resistances R_{pol}. The voltage distribution along the string is now greatly influenced by the pollution layer. Surface currents cause certain

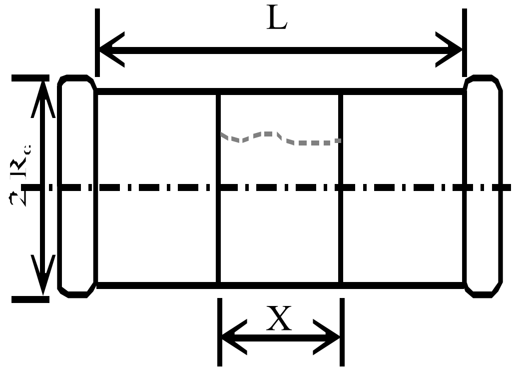


Fig. 3.32: Polluted Insulator with a dry

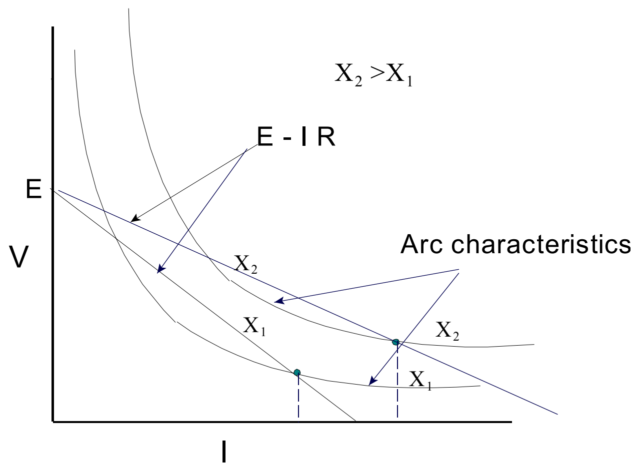


Fig. 3.33: V-I characteristics of polluted layer and dry band arc as dry band widens

Fig. 3.34: Polluted Glass Cap and Pin Insulator string with dry bands

regions on the surface of each disc to dry out, resulting in dry bands around the insulator.

The voltage across these bands cause sparks and arcs across the bands as shown in Fig. 3.32. The creepage length of the insulator is L and the dry band and arc length is X.

The pollution flashover process can be modelled, using an equivalent circuit consisting of the arc across the dry band in series with the linear resistance of the pollution layer. The interaction of the components of this circuit can be analysed, using the graphical representation, shown in Figure 3.33. This analysis is rather complex as both components change with the dry band length. Under certain conditions the partial arcs may extinguish as no point of intersection exists between the arc and pollution layers.

Under other (heavily polluted) circumstances the arc may grow to such an extent that the insulator flashes over. An insulator string with arcs over the dry bands, during a laboratory test, is shown in Fig. 3.34. The AC flashover voltage of an insulator may be reduced by as much as 80 per cent.

The flashover voltage of a polluted insulator may be estimated by theories, based on the mechanism outlined in Figures 3.32 and 3.33. It has been shown by Verma that the probability of flashover becomes high, should the leakage current exceed a critical level. This level has been found to be:

$$I_c = (SLC/15.3)^2 \tag{3.22}$$

In this equation SCL is the specific creepage length, given by :

(Creepage length of insulator)/ (System line to line voltage)

The creepage length of the insulator is the length from the live side to earth when following the insulator profile.

For a cylindrical insulator, such as the one shown in Fig. 3.32, assuming a uniform pollution layer, the pollution flashover voltage can be shown to be

$$V_c = \frac{NL}{(n+1)}\left[\frac{r_p}{N-A}\right]^{\frac{n}{n+1}} \tag{3.23}$$

In this equation N, A and n are arc constants and r_p is the quotient of the total pollution resistance and the creepage length. Usual values for the constants are N=80, A=10 and n=0.5 if the units are mm and V.

For the case of an insulator with an irregular practical shape, such as a cap and pin insulator, r_p is given by:

$$r_p = \frac{F}{L\sigma_s} \tag{3.24}$$

with F the form factor, L the creepage length and σ_s the surface conductivity in microsiemens. The form factor of an insulator is given by:

$$F = \int_0^L \frac{1}{2\,\pi\, r(s)} ds \qquad (3.25)$$

with

L: creepage length

s: position as measured along insulator profile (along shortest leakage current path)

r(s): radius at position *s*

A typical value for F for one cap and pin disc is 0.7. The value of the surface conductivity depends on the pollution severity, as given in Table 3.6

When the appropriate constants are used in equation 3.23 together with equations 3.24 and 3.25, the following useful formula for the calculation of the flashover voltage of insulators is obtained:

$$V_c = 7.6 \cdot 10^{-3} L \left(\frac{F}{L\sigma_S}\right)^{0.35} \qquad (3.26)$$

with V_c in kV, L in mm and σ_s in μS

Exercise:

A cap and pin insulator disc has a form factor F = 0.7 and a creepage length L = 280 mm. Calculate its pollution flashover voltage if the surface conductance is σ_s= 25 μS (medium pollution). Comment on the use of 6 such discs on a 66 kV system in an area with medium pollution.

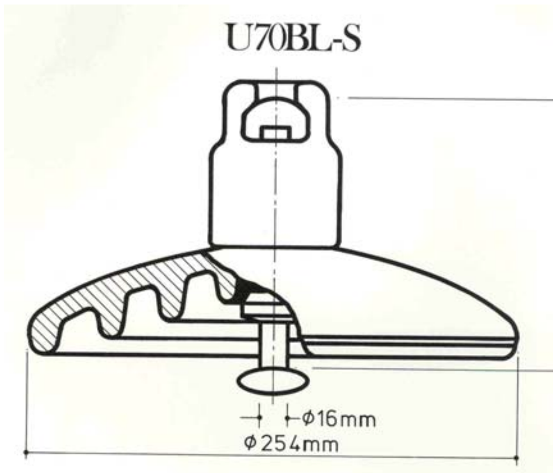
(Answer: 10.66 kV phase to neutral; The withstand voltage of 6 discs would be 64 kV, as opposed to the 1.1*66/√3 =42 kV highest voltage appearing on the 66 kV system – thus acceptable.)

Table 3.6: Withstand surface conductivities and corresponding recommended creepage lengths:

Pollution Class	Withstand Surface Conductivity (μS)	Specific Creepage length	
		AC (mm/kV line to line)	DC (mm/kV)
Light	<6	16	20
Medium	6 - 12	20	24
Heavy	12 - 24	25	31
Very Heavy	> 24	31	38

3.4.1 Form Factor Calculation

The approximate evaluation of the integral in eq. (3.25) can be done by measuring the radius at various positions along the creepage path, typically on an insulator such as



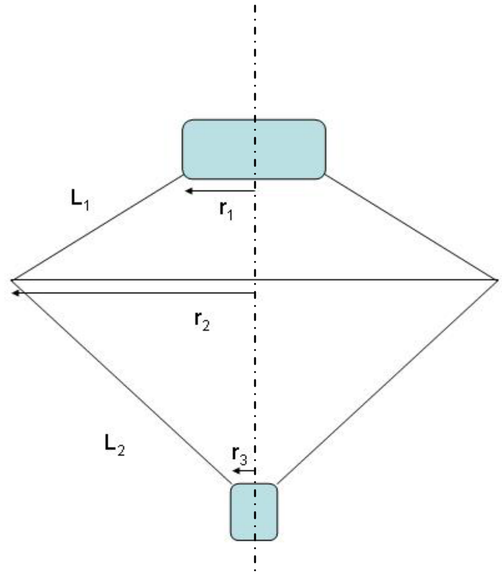


Fig. 3.35: (a) Typical cap and pin insulator. (b) Simplified model of Insulator

shown in Fig. 3.35 (a) and using this data as inputs to a numeric integration procedure.

Another approximate approach is to represent the surfaces of the insulator of Fig. 3.35 (a) by a model consisting of two cones, having an outside radius r_2, equal to the outside radius of the actual insulator. The upper cone has a surface length, L_1, equal to the creepage length along the top of the actual insulator. Likewise, the lower cone represents the bottom of the actual insulator, having a creepage length of L_2. The radius r_1 is made equal to the radius of the cap of the actual insulator and the radius r_3 is equal to the radius at the pin area of the actual insulator.[4]

It can be shown that the form factor of a cone, such as the upper one, is given by:

$$F_1 = \frac{L_1}{2\pi(r_2 - r_1)} \ln(\frac{r_2}{r_1}) \qquad (3.27)$$

Consequently, the form factor for the disc of Fig, 3.35 (a) is given by:

$$F = \frac{L_1}{2\pi(r_2 - r_1)} \ln(\frac{r_2}{r_1}) + \frac{L_2}{2\pi(r_2 - r_3)} \ln(\frac{r_2}{r_3}) \qquad (3.28)$$

---

[4] In the case of a cap and pin insulator the cement is considered to be conducting and part of the electrode.

In the case of a standard glass disc: r_1 = 36, L_1=95, L_2=175, r_2 = 127 and r_3=18 mm.
This yields: F=0.71
The form factor of a string, consisting of *n* identical units, each having a form factor *F*, is *n F.*

The form factor of long rod and other insulators can also be evaluated by dividing the insulator into conical and cylindrical sections.
The form factor contribution of a cylindrical section having a length *L* and a radius *R* is given by:

$$F = \frac{L}{2\,\pi\,R} \tag{3.29}$$

The form factor of the complete insulator is obtained by adding the form factors of the various sections.

3.5 Summary of Properties of Typical Insulating Materials

Table 3.7 gives an overview of the properties of the main insulation types.

Table 3.7: A comparison of the various types of insulating materials

	Air	SF_6	Solids	Liquids
Dielectric constant	1	1	3-6	2 - 4
Dielectic strength (kV/cm)	30 (at 1 bar)	120 (at 4 bar)	200 - 400	240
Advantages	- Can flow - Self-restoring - Abundant	- Can flow - Self-restoring - High dielectric strength - Good arc quencher in circuit breakers	- Can support conductors - High dielectric strength - Some types can be moulded (epoxies)	- Can flow - Can be cleaned/ recirculated and be replaced - Can be used as coolant - circulated
Disadvantages	- Low dielectric strength - Low dielectric constant a problem when used in series with solid or liquid insulating materials	- Hot house gas - Breakdown products toxic	- Not self-restoring - Can not fill small spaces	- Absorbs moisture - Affected by impurities

3.6 Review Questions

1. The Geiger counter is used to detect radioactive radiation. It utilises gas discharges in the non-self-sustaining region as described in section 3.1. Describe its operation. Use the Internet as a resource.
   (Ans.: See e.g.: *http://www-istp.gsfc.nasa.gov/Education/wgeiger.html)*
   (5)
2. Explain, briefly, avalanche formation due to the collision mechanism (section 3.2). Avoid a detailed mathematical formulation.
   One electron is released at the cathode (Fig. 3.1). The field strength between the electrodes is 3000V/mm. Estimate the number of electrons (and positive ions) in an avalanche of length 50 mm. Use eqs. (3.3), (3.1). Use A= 15 ion pairs cm^{-1} (mm $Hg)^{-1}$ and B = 365 V cm^{-1} (mm $Hg)^{-1}$ Assume normal atmospheric pressure (100 kPa = 1 bar = 760 mm Hg).
   (Ans.: 244 electrons)
   (10)
3. Explain, briefly, the transition from a non-self-sustaining Townsend discharge to a self-sustaining discharge.
   The breakdown voltage of a uniform field gap of 0.1 cm is 4500 V. Calculate the secondary coefficient of ionization (γ) if the gas is air at a pressure of 760 mm Hg and the temperature is 25 degrees C. Use A=15 cm^{-1} and B = 365. (Use the theory in section 3.2).
   (Ans.: γ = 0.1 ionisation per cathode collision)
   (10)
4. Eq. (3.4) is an empirical representation of Paschen's Law. Use this formula to calculate the flashover voltage of a 300 mm uniform gap at (i) sea level (ii) in Johannesburg, 1200 m above sea level. Assume that the air pressure is reduced by 10 mm Hg for every 120 m increase in altitude. The atmospheric pressure at sea level is 760 mm Hg (1bar = 760 mm Hg).
   (Ans.: sea level: 767.6 kV; Jhb.: 668.9 kV)
   (10)
5. Explain streamer discharges.
   An avalanche becomes unstable and streamer formation starts when the number of ionizations approaches 5.10^8. Estimate the length of an avalanche that was started by a single electron under the following conditions; E = 30 kV/cm, p= 760 mm Hg. Use A= 15 (cm.mm $Hg)^{-1}$, B= 365 V/(cm.mm Hg). (Hint: use a trial and error method).
   (Ans.: d= 18.2 cm)
   (10)

6. Why is SF_6 a better insulating medium than air at the same pressure?

   An empirical formula for the flashover voltage for SF6 in a homogeneous field (similar to eq. 3.11 for air is : $V_b = 40 + 68\ pd$ (units: kVpeak, cm, bar)). A uniform gap is required to withstand 630 kV rms in a GIS (SF6 gas insulated system), using a pressure of 5 bar. What is the minimum gap length if it is assumed that the flashover voltage is twice the withstand value? Compare the value with that if air is used at the same pressure.

   (Ans.:SF_6: d=2.5 cm, air: 7 cm)

   (10)

7. Calculate the corona inception gradient of a stranded ACSR (Aluminium Cable Steel Reinforced) conductor of 20 mm diameter, using Peek's formula, if it is to operate at an altitude of 1200 m above sea level at ambient temperatures as high as 35 degrees C. Assume a roughness factor of m = 0.8. Assume that the air pressure is reduced by 10 mm Hg for every 120 m increase in altitude. The atmospheric pressure at sea level is 760 mm Hg. If this conductor is used in a concentric busbar system with a 50 cm radius for the outer cylinder, calculate the corresponding corona inception voltage (rms).

   (Ans.: 27,84 kV (peak)/cm, 77 kV rms)

   (10)

8. What are the differences between a) Townsend discharges, b) Streamer discharges and c) Leader discharges? Describe briefly the main characteristics of each and the conditions under which each phenomenon occurs.

   (10)

9. Why is it preferable not to have severely non uniform fields in an apparatus, such as a transformer, that uses oil as its main electrical insulation material? Comment on the use of insulating shields (barriers) in power transformers.

   (5)

10. Consider a cavity in a dielectric sample as is shown in Fig. 3.25(b) in the notes. The dielectric constant of the dielectric is 4 and the thickness of the void is 1 mm. The specimen is 10 mm thick and is subjected to 15 kV (rms). The void is filled with air with a breakdown strength of 30 kV (peak) /cm. Find the field strength in the void. Derive formula from first principles (given $\varepsilon_1 E_1 = \varepsilon_2 E_2$). Discuss the implications of the calculated value and show how this type of discharge can lead to eventual failure of a high voltage apparatus such as a high voltage cable, using polythene as main insulation. What precautions/techniques are necessary during manufacture?

    (Ans.:65.27 kV/cm peak)

    (10)

11. The set-up shown in the adjacent Figure is used to determine the puncture stress of the dielectric slab having a dielectric constant of 4. Comment on surface discharges that may possibly form prior to failure of the sample. How can the surface discharges be avoided? What are the long term effects on HV equipment of surface discharges? (Hint: draw the field lines first).

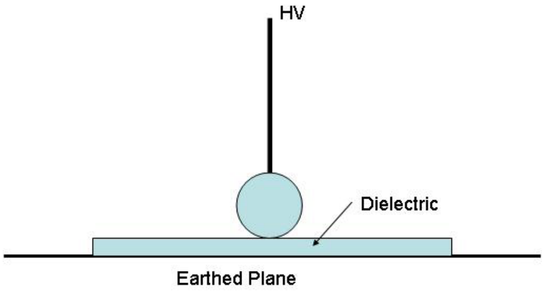


Fig. 3.36: Diagram for Q. 11

(10)

12. Fig. 3.37 (a) shows a schematic presentation of a 132 kV single core cable (one phase) buried in soil. The cable is buried at a depth of h= 1 m, the outside radius of the cable is R = 30 mm and the conductor radius is r1 = 10 mm. The cable has an ohmic resistance of 55 micro-ohm/metre and carries a current of 500 A. The thermal resistivity of the soil is ρT = 1.2 °C m/W and that of the dielectric is ρT = 5 °C m/W . The dielectric has a dielectric constant of 3.5 and a tan δ of 0.02 (an unusually high value). Assume that the RI^2-losses are generated in the conductor, and that the dielectric losses are concentrated in the middle of the dielectric, i.e. at the radius r2= 20 mm. Compute:

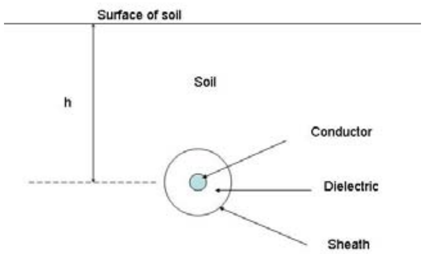


Fig. 3.37(a): Cable in soil

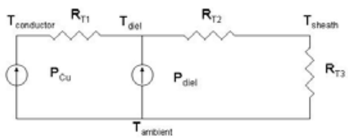


Fig. 3.37 (b): Equivalent circuit

a) The capacitance of the cable. (177 pF/m)

b) The dielectric loss per metre. (6.47 W/m)

c) The RI^2-losses / metre.(13.75 W/m)

d) The thermal resistances per metre of the two regions of the cable. (0.55 and 0.32 °C m/W))

e) The thermal resistance per metre of the soil from the sheath to the ground surface.(0.802 °C m/W)

f) The temperature rise above ambient (the soil surface) of (i) the cable core, (ii) the centre of the dielectric and (iii) the sheath of the cable. (28.24, 20.65 and 16.21 °C)

Hint: Use the electric/ thermal analogy of section 2.5 in the notes and the following formulae for the thermal resistances, as in Fig. 3.37(b):
in the cable:

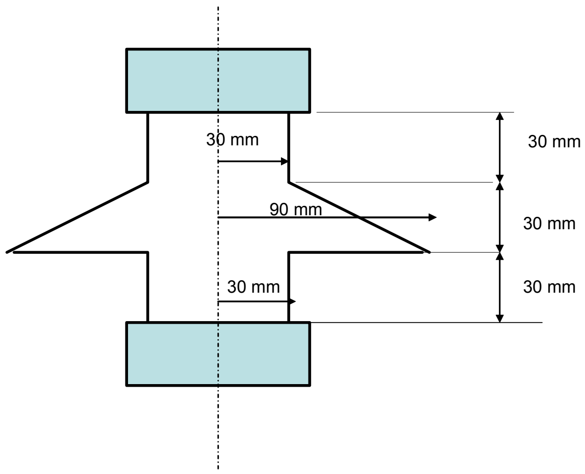
$$R_T = \rho_T \frac{\ln(R/r)}{2\pi} \quad °C/(W\,m)$$

and in the soil:

$$R_T = \rho_T \frac{\ln(2h/R)}{2\pi} \quad °C/(W\,m)$$

13. Explain how contamination of the surface of an insulator may lead to flashover. A cap and pin insulator disc has a form factor F = 0.7 and a creepage length L = 280 mm. Calculate its pollution flashover voltage if the surface conductance is σ_s = 25 μS (very heavy pollution). Comment on the use of 6 such discs on a 66 kV (line-to-line) system in an area with medium pollution. (Ans.:11.9 kV rms).

14. Calculate the form factor of the insulator shown in the adjacent figure.
(Ans.: F=0.354)



4 HIGH VOLTAGE TESTING AND MEASUREMENT

Benjamin Franklin: The man who dared to fly his kite in a thunder storm …

In the previous chapters the insulation characteristics of materials under high voltage stresses were discussed. It was seen that overstressing leads to failure of the equipment. In this section laboratory tests and test equipment needed to assess the performance of materials and equipment relative to the specifications are discussed. The different methods to accurately measure high voltages are also discussed. The actual stresses that may occur on the power system will be dealt with in Chapter 5.

4.1 Generation of High Voltages

Laboratory testing attempts to simulate the voltage conditions that the apparatus may experience on the power system. These voltages include the normal AC or DC system voltages and switching and lightning impulse voltages. Tests can be performed to obtain the failure or flashover voltage or otherwise to obtain the withstand voltage of an apparatus.

4.1.1 Power frequency voltage and current (AC)

In an AC network the equipment is continuously subjected to full power frequency voltage. The equipment should therefore be able to withstand power normal frequency voltage, allowing for some overvoltage.

In a high voltage laboratory the test transformers steps up the voltage from a lower voltage (220 V or 11 kV) to the desired voltage level. All laboratory tests are single phase and the low voltage side of the transformer is supplied via a regulating transformer to be able to adjust the magnitude of the output high voltage. A typical AC high voltage set-up is shown in Fig. 4.1.

The following features should be noted:

- *Ground plane*: The high voltage is generated with respect to the laboratory ground, a low impedance sheet, connected to an earth electrode.
- *Voltage divider*: The voltage is measured with a resistive or capacitive voltage divider as is described in section 4.2.1.

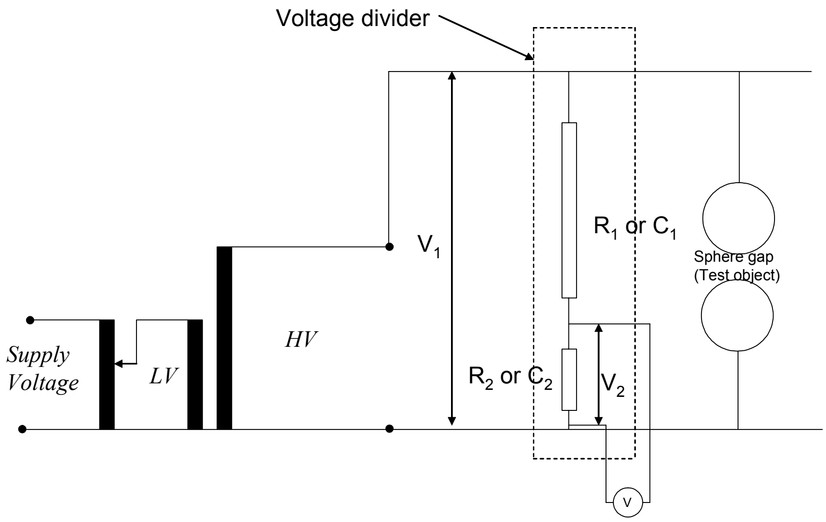


Fig. 4.1: Schematic diagram of a typical AC test transformer and its connections.

Typical designs of high voltage test transformers are shown in Fig. 4.2(a). In the design on the right an insulated tank (a resin impregnated paper cylinder) is used and a bushing is not required, as is shown in Fig. 4.2(b).

Test transformers can be used in cascade connections as is shown in Fig. 4.3. Each unit has 3 windings: a primary (low voltage), a secondary (high voltage) and a tertiary (low voltage) winding. The tertiary has the same rating as the primary winding; however, it is insulated for high voltage. The tertiary winding is used to supply the primary of the next unit. The tanks of the second and third units are insulated for high voltage and are mounted on insulators.

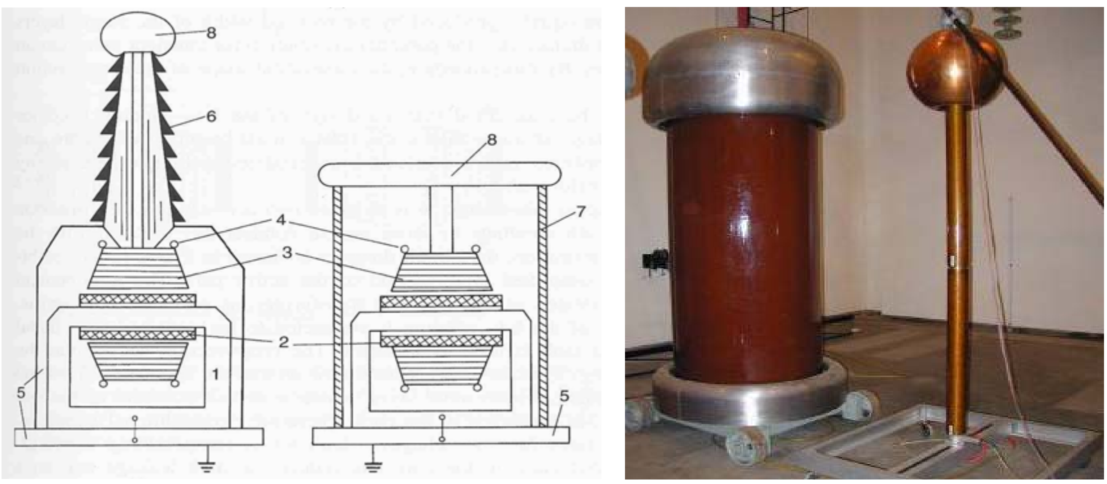


Fig. 4.2: Typical designs of AC test transformers

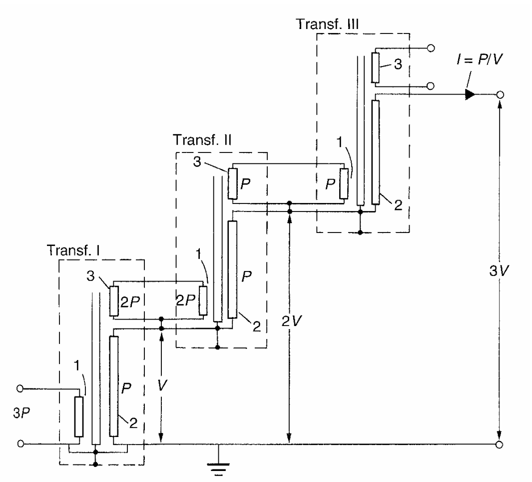


Fig. 4.3: Cascade connected test transformers

The method when performing AC tests is to increase the voltage gradually until flashover occurs. The voltage just before flashover is the flashover voltage.

4.1.2 Direct current (DC)

DC tests are used mainly to do "pressure tests" on high voltage cables. Although the cables operate with AC, AC testing is not practical. The high capacitance of the cables necessitates AC test sets with a high kVA rating to be able to supply the capacitive current. In the case of DC, once the cable is charged, only the losses have to be supplied.

DC test sets usually consist of half wave rectification, using HV selenium rectifiers. A typical DC test set-up is shown in Fig. 4.4.

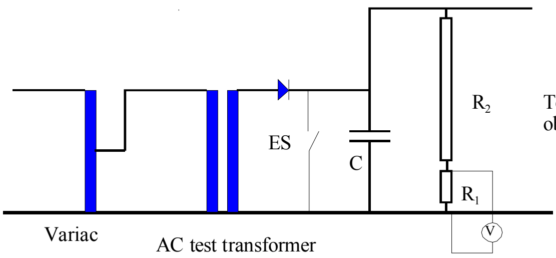


Fig. 4.4: Typical circuit for DC tests

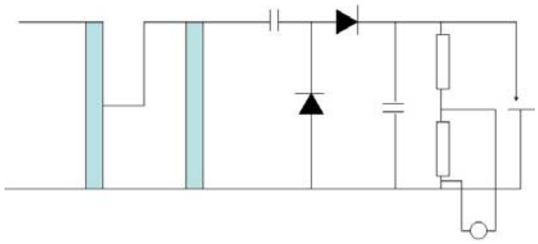


Fig. 4.5: Typical doubling circuit for DC tests

An AC high voltage test transformer is again supplied via a variac and a rectifier is used together with a filter capacitor C to limit the ripple to acceptable values. The earthing switch ES is a safety feature and closes automatically when the power is switched off to discharge the capacitor C. Note that the peak inverse voltage required of the rectifier is 2 V_m.

Doubling and multiplier circuits (as used in TV's and household appliances) are also used to obtain an even higher voltage. A typical Cockcroft-Walton (in Germany: Greinacher) doubling circuit is shown in Fig. 4.5.

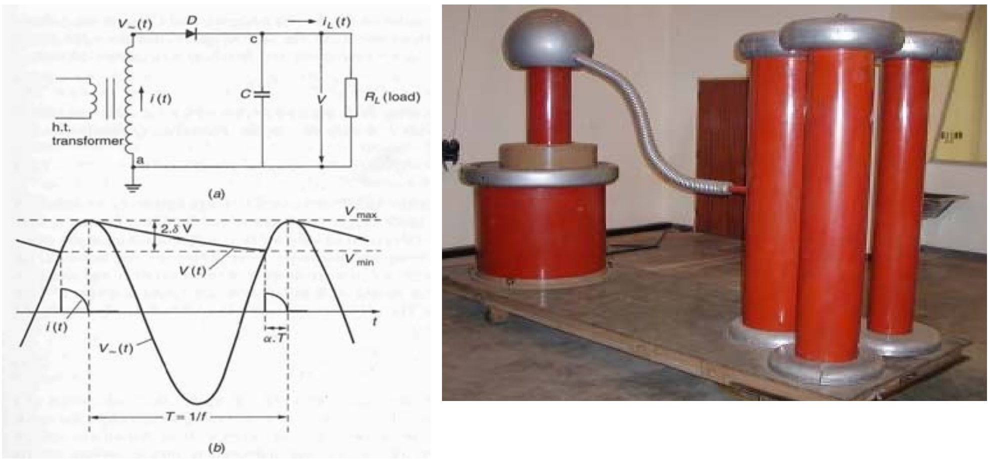


Fig. 4.6: Typical waveforms and a typical doubling circuit DC test source

4.1.3 Lightning and switching impulses

In chapter 5 it will be shown that the power system is also subjected to single overvoltage pulses, due to lightning and switching. In the field these transients can take on many different wave shapes. Standard impulse wave has been defined as shown in Fig. 4.7. The actual definition is more precise, but for lightning impulses, T1 is 1.2 μs and T2 is 50 μs. The standard lightning impulse is described as a 1.2/ 50 μs wave. The standard switching impulse is a 250/ 2500 μs wave.

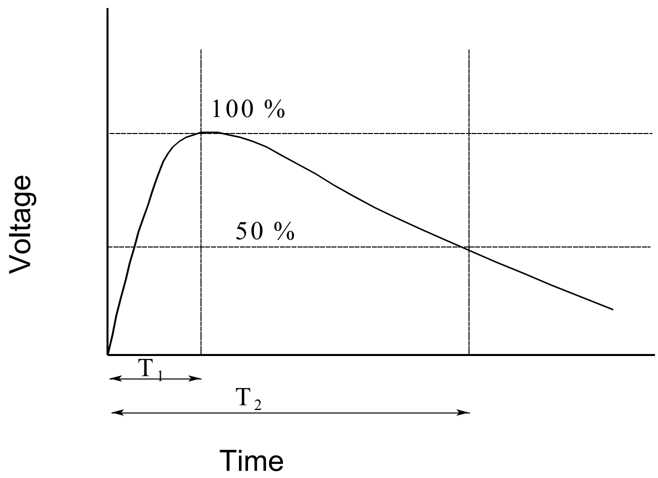


Fig. 4.7: Standard impulse wave

During transformer tests it is sometimes required to chop the impulse to obtain a high *dv/dt*, in order to test the inter-turn insulation.

The Impulse generator

In order to generate a wave with the required shape, circuits similar to that shown in Fig. 4.8 are used. A capacitor C_1 is charged via a current limiting resistor, R_s, from a HV dc source similar to those shown in Figs. 4.4 and 4.5.

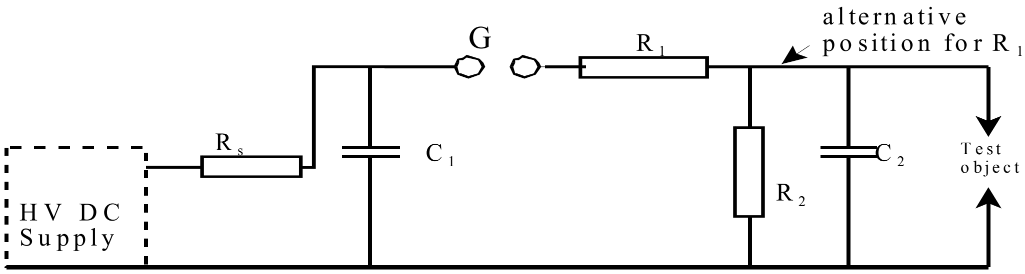


Fig. 4.8: Single stage impulse generator

As the DC voltage is raised slowly the stress across the spark gap G increases until the air in the gap breaks down. Capacitor C_1 now discharges into the circuit consisting of C_2, R_1 and R_2. The voltage appearing across the test object has the desired shape. The components C_1, C_2, R_1 and R_2 are chosen to give the required front and tail times. It turns out that $C_1 >> C_2$ and $R_2 >> R_1$. Capacitor C_1 will recharge via R_s and repetitive pulses will be generated.

There are two possible positions for R_1 as is shown in Fig.4.8.

It is possible to design a multi stage impulse generator by charging the various stages in parallel and by discharging in series. This principle was invented by Marx in 1923. A typical circuit is shown in Fig. 4.9.

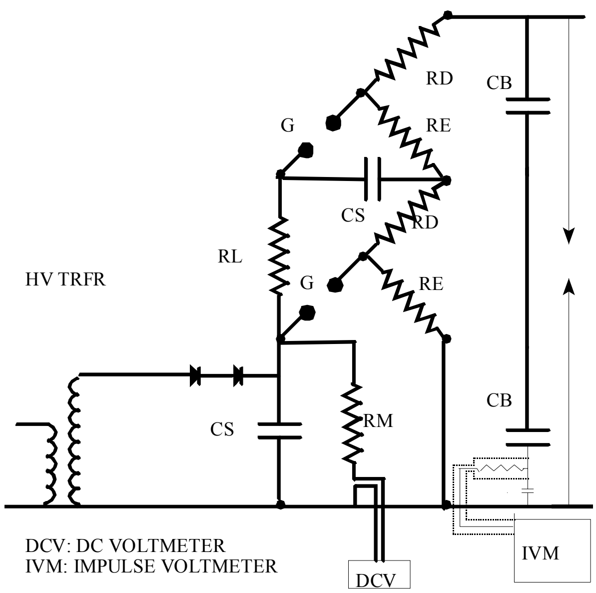


Fig. 4.9: Two-stage impulse generator

Note that it is possible to trigger the lowest gap of the generator artificially. The resulting transient causes the other gaps to flash over simultaneously.

Impulse generators are specified in terms of the peak voltage and the stored energy. The generator shown in Fig. 4.10 is a 1.4 MV, 16 kJ generator.

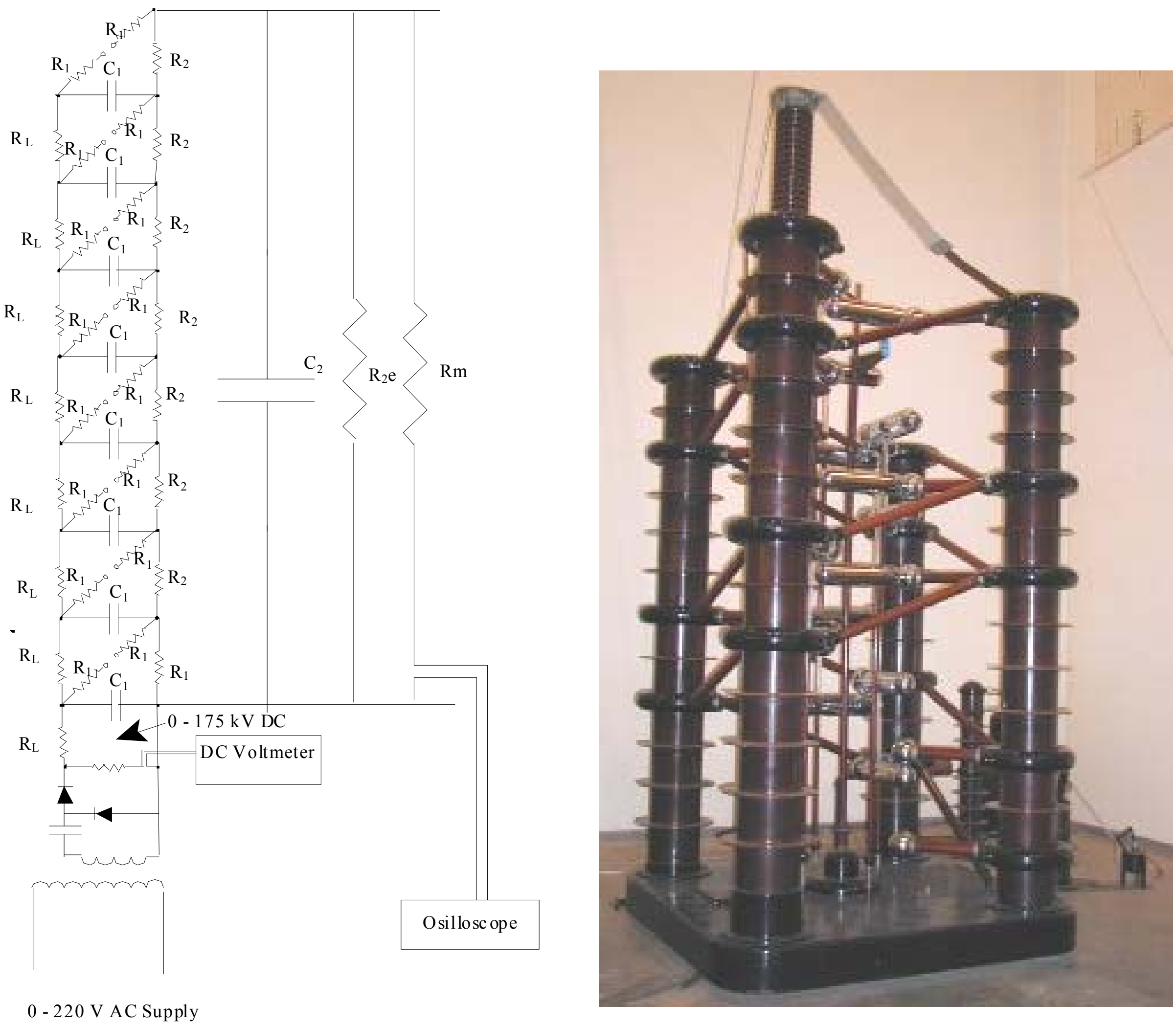


Fig. 4.10: 8- stage impulse generator

4.2 Measurement

Lord Kelvin (William Thomson, 1824 – 1907) wrote, "To measure is to know" and, "If you can not measure it, you can not improve it." Accurate measurements are likewise the key to successful testing and research. The problem with high voltage is, however, that, due to safety reasons, the meters can not be connected directly to the high voltage conductors. It is therefore necessary to use equipment to scale down the voltage signal to a safe value that can be displayed on instruments. On the power system, voltage and

capacitive voltage transformers are used (section 1.3.5), while voltage dividers are used in the laboratory. Obviously, accuracy of the whole system is of the utmost importance.

4.2.1 Voltage dividers

The operation of voltage dividers depend on the division of voltage across two series impedances, Z_1 and Z_2, as shown in Fig. 4.11. In this figure:

$$V_2 = \frac{Z_2}{Z_1 + Z_2} V_1 \qquad (4.1)$$

In this equation $Z_2 << Z_1$, resulting in V_2 being a scaled version of V_1. The nature of Z_1 and Z_2 depends on the type of voltage to be measured, as is shown in Table 4.1.

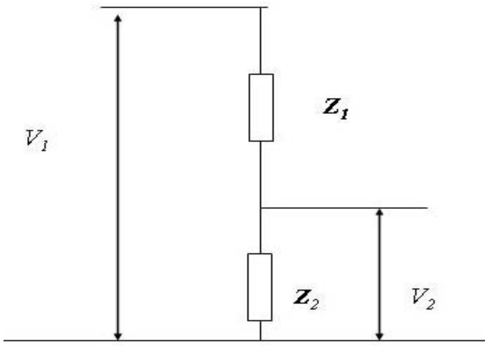


Fig. 4.11: General voltage divider

Table 4.1: Voltage dividers for different types of voltages

Type of voltage	Nature of the impedances
DC	Resistors
AC	Resistors or Capacitors
Impulse	Resistors or Capacitors

AC and DC measurements

For a resistive divider:

$$V_2 = \frac{R_2}{R_1 + R_2} V_1 \qquad (4.2)$$

For a capacitive divider:

$$V_2 = \frac{C_1}{C_1 + C_2} V_1 \qquad (4.3)$$

The voltmeter is directly calibrated in terms of the high voltage. *The sphere gap* is used to calibrate the voltage measurement.

Impulse measurement

Impulse waves can be measured and displayed on an oscilloscope, using resistive or capacitive dividers.

Resistive impulse dividers

A resistive divider has distributed stray capacitance to ground that may affect the accuracy of high frequency measurements. As is shown in Fig. 4.12, this stray capacitance can be approximated by an equivalent capacitor, C_e, connected to the centre of the resistive column. It can be shown that $C_e = ⅔ C$ and that the time constant of the divider is:

$$\tau = \frac{1}{6} R_1 C_e \qquad (4.4)$$

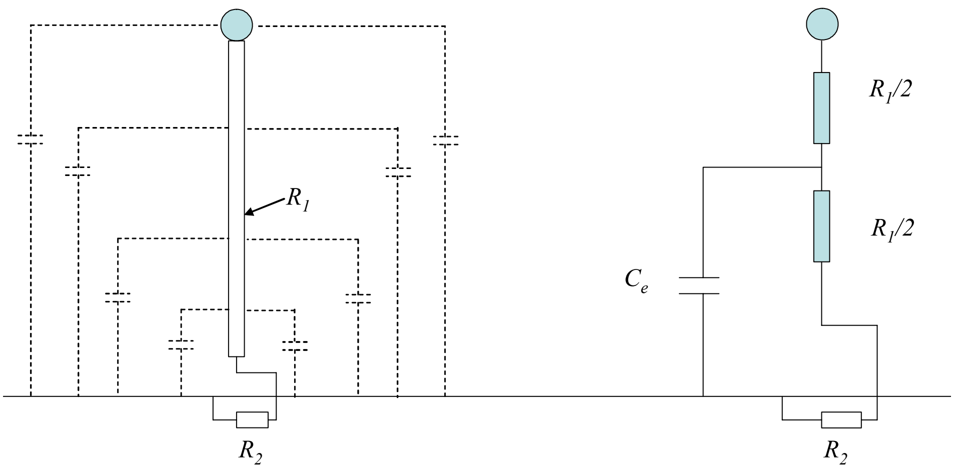


Fig. 4.12: (a) Stray capacitance of a resistive divider and (b) the equivalent circuit

The total capacitance-to-ground of vertical structures, such as dividers, are estimated at 15 to 20 pF/m height. Thus, a 1 MV divider, having a height of 3 m and a resistance of 20 kΩ would have a time constant of approximately 200 ns, only just adequate for a 1.2/50 μs wave.

Note that the coaxial cable must be terminated in its characteristic impedance at both ends, as is the case in the circuit in Fig. 4.13.

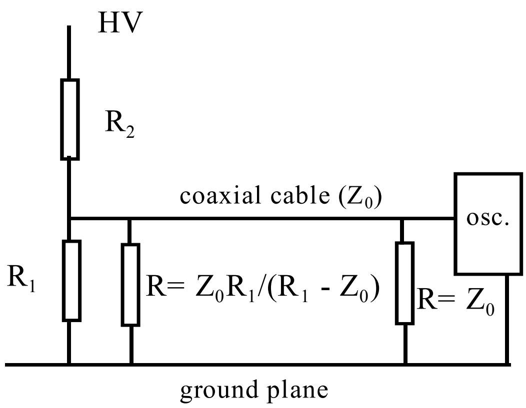


Fig. 4.13: Resistive impulse divider

Capacitive impulse dividers

In the case of a capacitive divider the stray capacitances are usually negligible, compared to the capacitance values of the divider.

Typical values for a 100 kV capacitive divider are C_1= 100 pF and C_2= 100 nF.
For the capacitive divider, shown in Fig. 4.14, the shunt resistor would allow the charge on C_1 to leak away and series matching must be used. The resistor R= Z_0 and the characteristic impedance of the cable forms a divider to halve the impulse when it travels along the line. At the oscilloscope, having a high input impedance, voltage doubling takes place and the original wave appears at the oscilloscope.

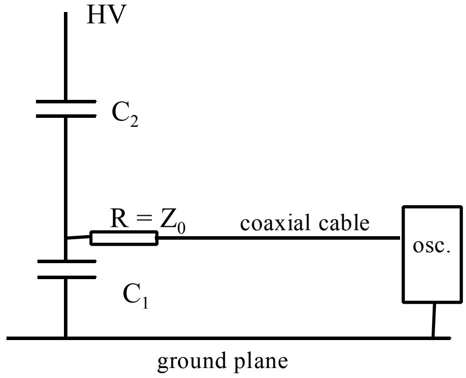


Fig. 4.14: Capacitive impulse divider

4.2.2 Peak and RMS voltmeters

Since flashover usually takes place at the peak of the AC wave, it is necessary to measure the peak and not the rms voltage (the voltage may deviate from a pure sinusoid). A typical circuit is given in Fig. 4.15, using a peak -hold circuit. Despite the fact that the metre measures peak, it is calibrated (scaled) in terms of $V_{peak}/\sqrt{2}$. The time constant RC should be low enough to allow the meter to follow variation in the supply voltage. The resistance R (includes the resistance of the voltmeter V) must be much larger than $1/(2\pi fC)$.

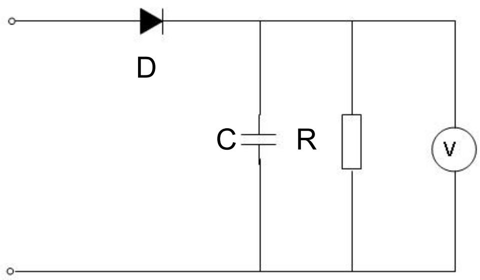


Fig. 4.15: Typical AC peak voltmeter circuit

4.2.3 Sphere gaps for voltage measurement

Paschen's Law indicates that there exists a relationship between the flashover voltage, the gap length and the gas density (section 3.1.5). International standards have therefore been drawn up to relate the gap length with flashover voltage. Provision has been made to correct for air pressure and temperature. Usually an accuracy of about 3 % can be obtained. Specifications such as IEC 52-1960 contains tables for various sphere diameters and gap sizes.

4.2.4 Electrostatic voltmeters

Electrostatic voltmeters rely on the Coulomb force of attraction between two electrodes that have a potential difference between them. Such a measuring system has the advantage that the measurement relies on the laws of physics. In addition, the input impedance of the meter is capacitive. Especially in the case of DC, the meter therefore does not load the measured circuit.

4.3 Laboratory Testing

4.3.1 Interpretation of AC, DC and Impulse test results

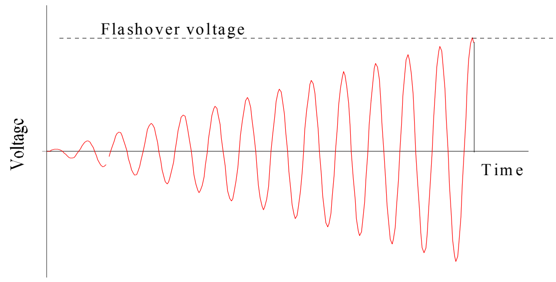


Fig. 4.16: AC flashover with increasing voltage.

With DC and AC tests the voltage across the test object is gradually increased until flashover. This is schematically portrayed in Fig. 4.16 for the AC case. The voltage, just before flashover, is taken as the flashover voltage. These tests are also performed on oil samples, using a 2.5 mm gap.

Flashover tests can be performed on air insulation, such as the flashover tests on power line insulators. More often, however, "non-destructive" withstand tests are performed, i.e. equipment must be able to withstand a specified withstand level for 60 seconds. The voltage is then increased up to the required voltage and kept at that value for 60 s.

Impulse tests are however more difficult to interpret. As shown in Fig. 4.17, the result of a test is either a flashover or a withstand (no flashover). A large impulse will cause a flashover on the front of the impulse. Flashovers are also possible on the tail of the impulse, although not shown.

It is also important to note that flashover is a statistical phenomenon as it depends on the availability of initialising electrons and other environmental influences. Even with AC and DC tests, a certain statistical variation is to be expected. With impulse testing, the critical flashover value as shown in Fig. 4.17 is not well-defined. In consecutive tests near this value on the same gap, some tests will result in flashover and others in withstand. The critical flashover voltage (CFO) is therefore defined as the 50 % flashover voltage. Out of 10 tests, an impulse with a peak value equal to the CFO will result in 5 flashovers and 5

withstands. This can also be seen from Fig. 4.18 where the flashover probability is shown as a function of impulse voltage.

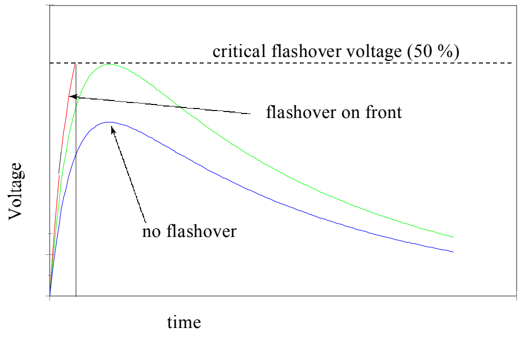


Fig. 4.17: Impulse flashover – time to flashover

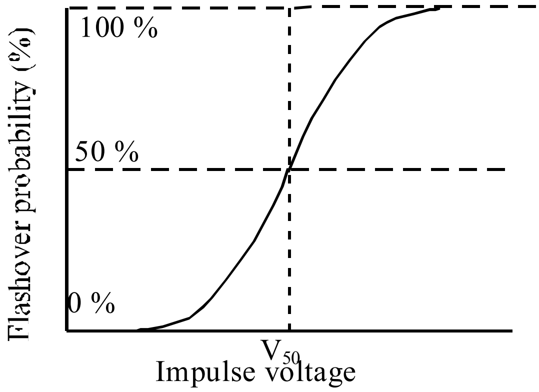


Fig. 4.18: Impulse flashover probability.

4.3.2 Non-destructive tests

Measurement of tan δ and capacitance with the Schering bridge

It was shown in section 4.2 that the loss factor, tan δ, is an indication of the quality of solid or liquid dielectrics. Measurement of tan δ of apparatus, such as high voltage current transformers provides a non-destructive indication of the quality of the insulation.

The capacitance and tan δ of high voltage equipment is measured, by applying the test voltage to the specimen in a way that corresponds to the way the apparatus is normally energised. In the case of a current transformer the secondary winding and core, connected together, would form the lower terminal of Rx/Cx in Fig. 4.19 while the primary winding would be connected to the high voltage.

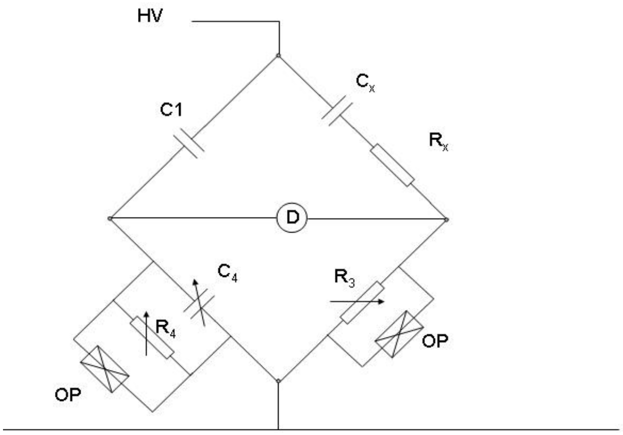


Fig. 4.19: Basic Schering bridge circuit

Although the usual model for an insulating material (dielectric) is a parallel RC circuit, as in Fig 3.18, it is possible to derive an equivalent series RC circuit (R_x and C_x in Fig. 4.19).

Capacitor C1 is a standard lossless capacitor, usually gas-filled with an accurately known capacitance (typically 92.926 pF). The "earth" sides of both C1 and Cx are connected to the low voltage arms of the bridge, housed in the resistor/capacitor box of the bridge. The magnitude of the impedance of these components are small relative to those of the HV components (C1, Rx, Cx), resulting in a low voltage across them.

The LV components are adjusted until the voltage between b and d is zero, as detected by the null detector, D. This condition occurs when:

$$\frac{Z_{ab}}{Z_{bc}} = \frac{Z_{ad}}{Z_{dc}} \quad (4.5)$$

leading to:

$$C_x = C_1 \frac{R_4}{R_3} \text{ and } R_x = \frac{C_4 R_3}{C_1} \quad (4.6)$$

Hence:

$$\tan\delta = \omega C_4 R_4 = \omega C_4 R_4 \quad (4.7)$$

The capacitance of the unknown sample, together with the loss factor is therefore known from these equations. Interpretation of measured tan δ values is assisted by experience. Typical values, pertaining to high voltage bushings are given in Table 4.1.

A typical implementation of a 60 kV Schering bridge is shown in Fig. 4.20.

Table 4.1: Typical permissible tan δ levels

Voltage (kV)	Tan delta (%)
11	7
22	5
66	2.5
88	2
132	1.5
275	1
400	0.5

Measurement of partial discharges

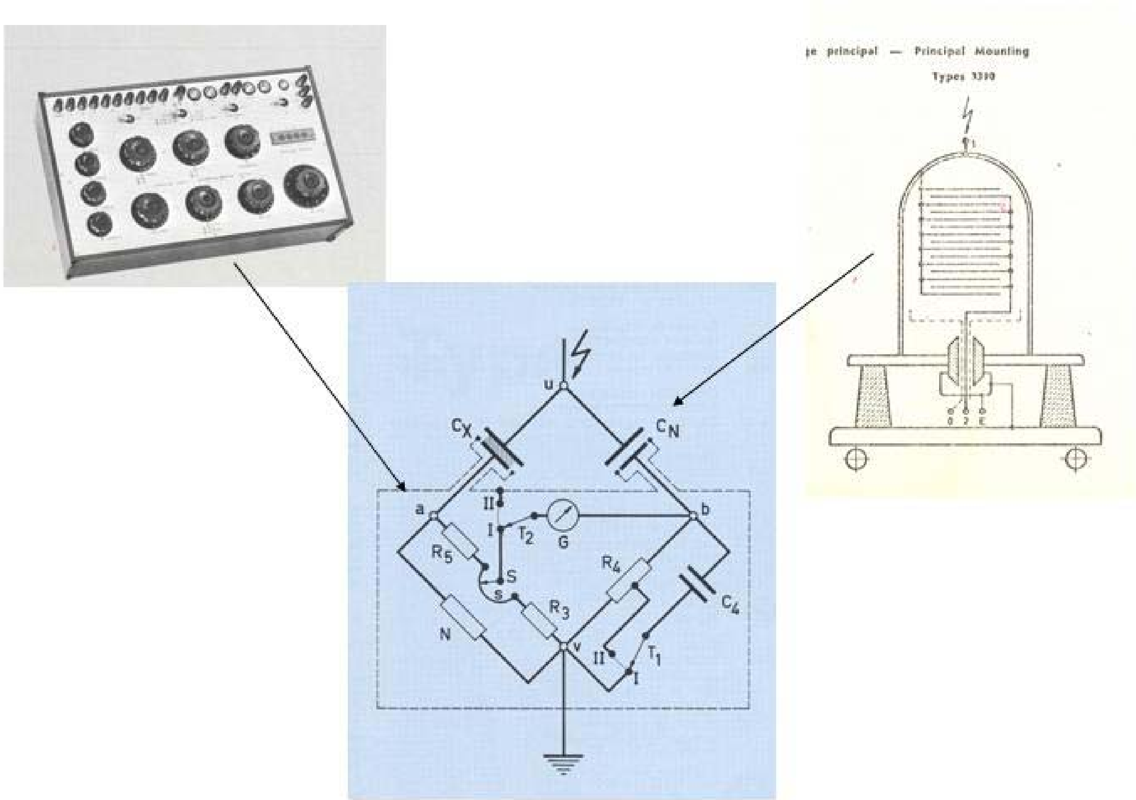


Fig. 4.20: Typical Schering Bridge set-up (Tettex)

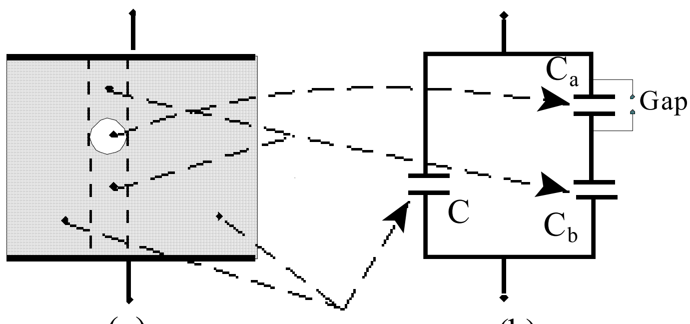


Fig. 4.21: Equivalent circuit for a void in a solid dielectric

As explained in section 3.3.2, discharges occur in voids in solid insulating materials. Consider a sample with a void as shown in Fig. 4.21. Note that the capacitance C represents the bulk of the sample, C_a that of the void and C_b the sections "in series" with the void.

The voltage waveforms, associated with Fig. 4.21 are shown in Fig. 4.22. Note that C_a and C_b form a capacitive voltage divider to give V_a the voltage of the air gap. When V_a reaches the breakdown value of the gas in the void, V_i, the voltage across the gap collapses. This collapse of voltage acts as a step wave and causes a charge displacement in the void. Note that, due to the inductance of the supply circuit, the capacitors cannot recharge from the source instantaneously and the voltage build-up follows the sinusoidal supply voltage.

Monitoring partial discharges with a discharge detector

The arcing inside the voids, shown in Fig. 4.22 causes impulse currents to flow. These currents would normally be supplied by the supply, but due to the high frequency nature of these currents, they would be suppressed by the inductance of the supply transformer.

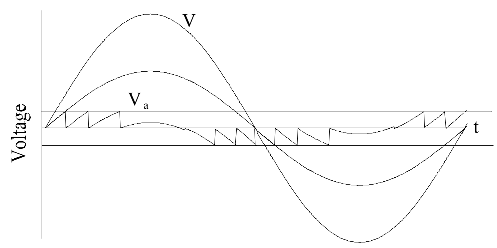
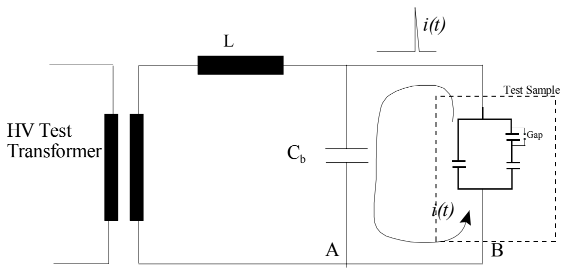


Fig. 4.22: Voltage waveforms relating to Fig. 4.21

In Fig. 4.23 a circuit is shown where a "blocking" capacitor is connected across the sample to permit the flow of the current impulses i(t). The impulse currents are then measured, using a filter unit as a detection impedance, in either position A or B as an indication of the partial discharge magnitude.



C_b: Blocking capacitor

Fig. 4.23: Discharge detector circuit

The circuit is designed to have a particular resonance frequency in the range 30 kHz to 100 kHz. The pulses are fed into a wide band amplifier and the output pulses are displayed on a CRT screen, superimposed on the supply sine wave to be able to detect the points on the wave where the discharges occur, relative to the zero crossings. The positive and negative half waves are often displayed as an

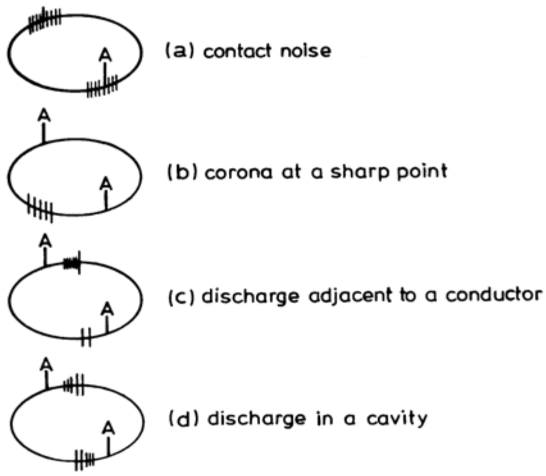


Fig. 4.24: Discharge detector display diagnostics

ellipse. Typical traces are shown in Fig. 4.24.

The discharge pulses are integrated with respect to time, giving the apparent discharges, measured at the sample terminals in picocoulomb (pC). The maximum acceptable discharge magnitude depends on the dielectric used in the equipment. Typical maximum acceptable levels for bushings are: oil impregnated paper = 10 pC, synthetic resin-bonded paper = 100 pC and cast resin = 20 pC.

4.4 Review Questions

1. In a single stage impulse generator employing the circuit of Fig. 6.6 of the notes, the components have the following values: C_1=10 000 pF, C_2= 1200 pF, R_1=375 ohm, R_2= 6100 ohm. Initially, the input capacitor is charged to 100 kV DC.

a) When G flashes over, C2 receives charge through the series circuit consisting of C1in series with R1 and C2 (ignore R2 as it is >> R1). Estimate the charging (RC) time constant (proportional to the front time).

b) Simultaneously C2 in parallel with C1 discharges into R2, causing the tail of the impulse. Estimate the discharge (RC-) time constant (proportional to the tail time). Ignore R1, as it is << R2.

c) How do these approximate time constants compare with those associated with a standard 1.2/ 50 μs wave?

d) Calculate the initial stored energy.

(*Optional:* Check the waveform, using PSpice modelling or similar.)

(Ans.: T1=0,4 μs, T2= 68 μs, time to peak = 2.08 μs)

(10)

2. a) Describe, briefly, the operation of the multi-stage impulse generator circuit given in Fig. 6.7 of the notes.

   b) Describe how the operator can vary the peak value of the impulse.

   c) Describe the concept: 50 % flashover voltage and indicate how you would determine it for a test sample, such as an insulator.

(10)

3. Describe the concept tan δ and describe how it is measured, using the circuit of Fig. 6.9 in the notes.
   During measurements on an oil sample with a Schering bridge, the following resistor and capacitor values pertain when the bridge is balanced: R3= 200 ohm, R4=258.27 ohm and C4= 0.012325 μF. The standard capacitor has a value of 92.926 pF. Compute the capacitance and the tan δ for the sample.

(Ans.:119.27 pF, 0.001)

A measurement with the oil removed, using the same electrode configuration yielded the following values at balance: R3= 200 ohm, R4=128.67 ohm and C4 = 0.0000 μF. Estimate the permittivity of the oil.(2.0)

(10)

5 OVERVOLTAGES AND INSULATION CO-ORDINATION

Lightning: The most awesome natural form of High Voltage seen by man …

In the previous chapters it has been shown that all the insulating materials that constitute the insulation system of an apparatus on the power system have finite strengths. The strength of an insulating item depends on the magnitude and duration of the maximum electric field strength in that item. The stresses are caused by overvoltages that occur on the system. For the system to be able to operate reliably, it is important that the strength of the insulation is coordinated with the stresses that may occur on the power system.

5.1 Insulation Co-ordination

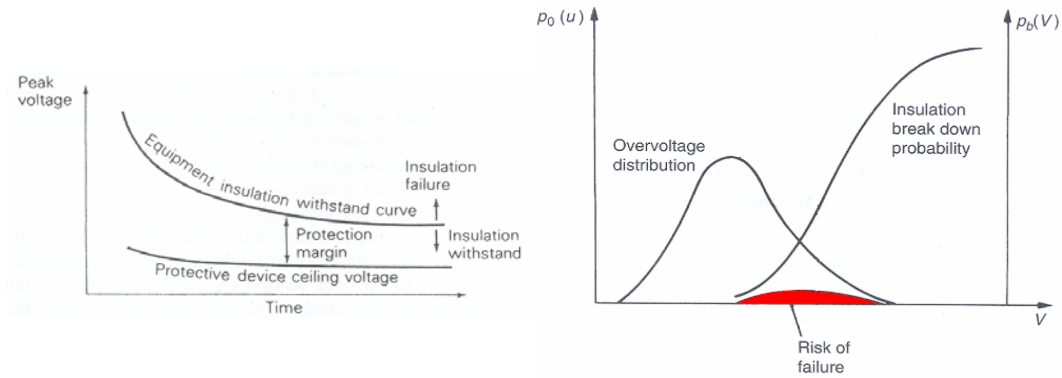
Insulation coordination is defined as: the correlation of the insulation of electrical equipment with the characteristics of protective devices such that the insulation is protected from excessive overvoltages. In practice, it means that an insulation level is determined for each voltage level to which the equipment is designed and tested. At the same time the system overvoltages are kept low by design efforts, such as proper grounding and shielding. Finally, the overvoltages are limited to the desired level by the application of lightning arresters or surge diverters.

5.1.1 Basic principles

The insulation in an apparatus has a certain withstand voltage/time characteristic as shown in Fig. 5.1(a). As shown in the figure, the overvoltage protection equipment has likewise a voltage/time characteristic. The protection level must be low enough to protect the apparatus with a “sufficient” margin. The size of the margin is a trade-off between reliability and cost. This is the conventional approach to insulation coordination.

In Fig. 5.1(b) the overvoltage *stress* is given as a statistical distribution function (d.f.) with the withstand *strength* a cumulative distribution function (c.d.f). The area of the product of the functions can be shown to constitute the risk of flashover. Reducing the magnitude of the overvoltages (by design or the application of protective devices) would move the overvoltage curve to the left. Similarly, would an increase of the withstand capability of the equipment move the strength curve to the right. A smaller risk of flashover would therefore result. The risk of flashover can typically, for a transmission line, be expressed as faults per km per

annum. The statistical method is the modern approach and can be based on actual test data, simulations and experience.



(a) *(b)*

Figure 5.1: (a): The concept of a deterministic protection margin and (b): The concept of a statistical risk of failure.

5.1.2 Standard insulation levels

As mentioned above, a standard impulse withstand value is chosen for each voltage level. Typical test values are given in Table 5.1. It will be noted that the apparatus must be able to withstand not only power frequency overvoltages, but also overvoltages due to lightning and switching. Switching overvoltages are only of importance for 300 kV and above as switching overvoltages are usually multiples of the normal system voltage and as the gap sizes at these voltages break down according to the leader mechanism (see section 3.1.7).

Table 5.1: Typical Standard Insulation Levels (IEC..)

Nominal and highest (in brackets) system voltage, U_m, kV_{rms}, line to line	**Standard power frequency short-duration withstand voltage kV_{rms}**	**Standard lightning impulse withstand voltage kV_{peak}**	**Standard switching impulse withstand voltage KV_{peak}**
6.6 (7.2)	22	75	_
11 (12)	28	95	_
22 (24)	50	150	_
66 (72.5)	140	350	_
132 (145)	275	650	_
275 (300)	460	1050	850
400 (420)	630	1425	1050

5.2 Power System Overvoltages

Overvoltages are voltages, appearing on the power system and exceeding the normal operating voltages. As noted before, these voltages can be power frequency, switching or lightning overvoltages. The magnitude of power frequency and switching overvoltages bear some relation to the system voltage. The magnitude of lightning overvoltages, however, is determined by the severity of the lightning stroke, together with the efficiency of the earthing and shielding methods.

These overvoltages are shown diagrammatically in Fig. 5.2, together with the different insulation levels, while typical magnitudes and durations are given in Table 5.2.

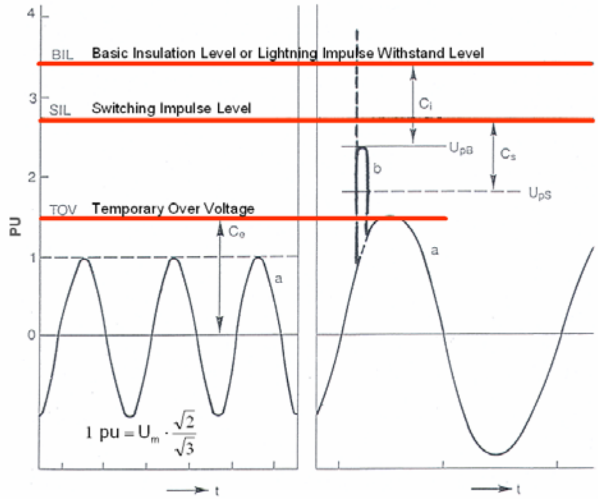


Fig. 5.2: Different types of overvoltage with corresponding insulation levels.

Table 5.2: Typical magnitudes and durations of the various types of overvoltage.

	Magnitude (p.u.),	**Duration**
Temporary (50 Hz)	1.5	50 s
Switching overvoltage	4.0	10 ms
Lightning overvoltage	6.5	100 μs

5.2.1 Power frequency overvoltages

As shown in Table 5.1, power system apparatus are specified to operate at U_m, which is usually about 5% higher than the nominal operating voltage. There are, however, circumstances where temporary overvoltages (TOV's) as high as 50% of the nominal voltage may occur. These overvoltages are extremely destructive due to their relatively long duration, as is clear from Table 5.2.

Temporary overvoltages are usually caused or triggered by some abnormal event on the power system. There are a variety of such causes and some are summarised in Table 5.3.

Table 5.3: Types of TOV's

Type	**Description**
Earth fault occurrence	Voltage increase due to method of neutral grounding.
Load rejection	Ferranti effect Generator loss of load
Line energizing and auto-reclosing	Travelling waves, trapped charge
Resonance effects	Resonance at fundamental frequency or harmonic frequency. Non-linear resonance between line capacitance and transformer magnetising reactance.

Some of these are discussed below:

Load rejection

The disconnection (shedding) of a large load leads to voltage increases on the system as the series resistive and reactive voltage drops disappear.

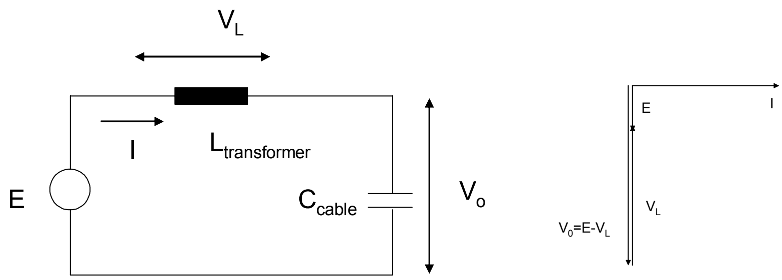


Fig. 5.3: Circuit and phasor diagrams for Ferranti effect (Note: V_0 > E)

The capacitance of an unloaded cable, in combination with a transformer or generator inductance may lead to an increase of the voltage at the end of the line, as is shown in Fig. 5.3. If the cable capacitance and the series inductance are in near resonance, the output voltage can be much higher than the input voltage, as can be seen in the phasor diagram.

This phenomenon is known as the Ferranti effect and can also be explained, using a distributed parameter model of a transmission line, resulting in the following equation:

$$\frac{V_0}{V_1} = \frac{1}{\cos(\beta\ell)} \tag{5.1}$$

with V_0 and V_1 the sending end and receiving end voltages of the line, respectively, ℓ the line length and β the phase constant of the line (usually 6° per km).

Earth fault occurrence: the effect of neutral earthing

If a ground fault occurs in a network with a non-earthed neutral, the healthy phases will adopt a √3 times higher voltage until the fault is cleared. If the system is earthed through an impedance, the overvoltage depends on the transformer neutral earthing impedance, as indicated in Fig. 5.4.

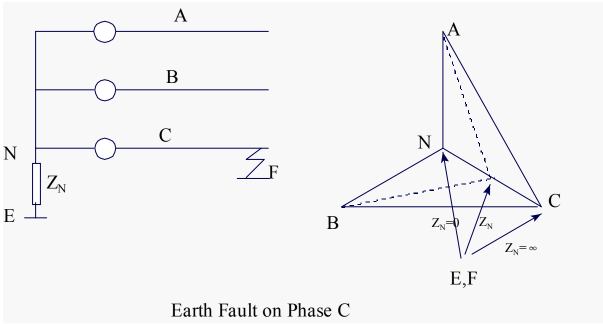


Fig. 5.4: The effect off neutral earthing on overvoltages

A system is classed as an effectively earthed system if $R_0/X_0 < 1$ and $X_0/X_1 < 3$, wherein

- R_0: zero sequence resistance
- X_0: zero sequence reactance
- X_1: positive sequence reactance

The overvoltage factor for earth faults (whereby the voltage prior to the fault occurrence has to be multiplied) is given by:

$$K = \sqrt{3}\,\frac{\sqrt{1 + X_0/X_1 + (X_0/X_1)^2}}{2 + X_0/X_1} \qquad (5.2)$$

In the above equation it was assumed that the system resistance can be ignored.

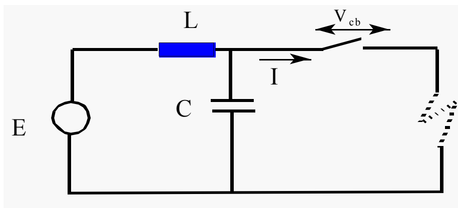


Fig. 5.5: The interruption of a fault current.

5.2.2 Switching overvoltages

A power system contains a large number of capacitances (mainly the line shunt capacitances and compensation capacitors) and inductances (e.g. transformer leakage inductances). During disturbances transients occur in the form of damped oscillations. Typical examples are:

- Fault clearing
- Transformer magnetising current
- Capacitance switching
- Energizing of unloaded transmission lines, travelling waves.

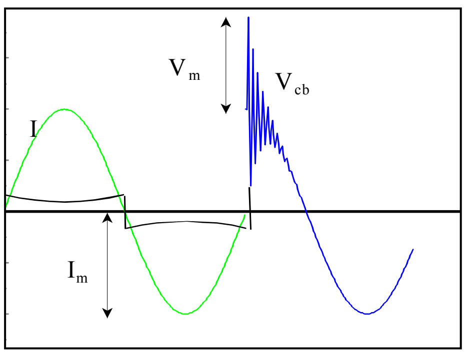


Fig. 5.6: The interruption of a fault current - waveforms

Only the interruption of fault currents will be dealt with here. Consider the power system in

Fig. 5.5. Sinusoidal fault current flows, only limited by the reactance L. When the circuit breaker interrupts the fault current at the current zero the voltage across the circuit breaker must recover to follow the supply voltage. The high frequency recovery voltage across the open circuit breaker contacts adds to the power frequency voltage and introduces additional stresses of the insulation of the power system components as is shown in Fig. 5.6. Clearly, a peak voltage as high as $2V_m$ may appear across the circuit breaker and thus also on the equipment, connected to the system.

The magnitude of the resulting overvoltage, should the current be "chopped" before the zero crossing, may be estimated by noting that the energy oscillates between L and C during the high frequency transient. For example, if the current is "chopped" at the current peak value, I_m, the energy in L , $W_L = \frac{1}{2} L I_m^2$, is transferred to C (ignoring losses), during the first cycle of the transient. The energy in the capacitor is:

$$W_C = \frac{1}{2} C v_m^2 \qquad (5.3)$$

Equating W_L and W_C, it follows that the maximum voltage across C is:

$$V_m = \sqrt{(L/C)I_m} \qquad (5.4)$$

Closing and tripping resistors that are inserted in parallel with the main circuit breaker gap for a short time during tripping, may effectively reduce switching overvoltages as is shown in Figure 5.7. The tripping resistors drain trapped charge from the line, while closing resistors damp oscillations that occur on energising a line.

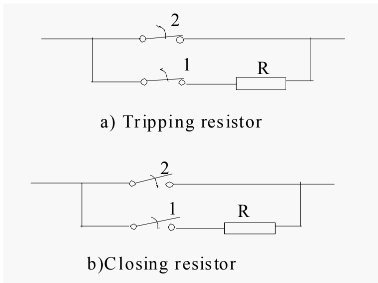


Fig. 5.7: Tripping and closing resistors.

Example 5.1:

In Fig. 5.5, E = 11 kV/ √3 rms, C = 1μF and L = 10 mH. Compute the peak overvoltage. Ignore losses.

Solution:

I_m = √2 11 000/(√3*2π* 50 *10* 10^{-3}) = 2859 A

Thus: V_m = ((L/C)) I_m= (10*10^{-3} / 1*10^{-6}) * 2859 = 28.59 kV.

5.2.3 Lightning overvoltages

Lightning overvoltages on the power system are caused by the large current that flows to ground during a lightning discharge from a cloud to earth. During such a discharge the object (e.g. a transmission line) could be part of the discharge path to ground (direct stroke)

or it could be indirectly affected by induced overvoltages. In order to understand the effects of lightning, it is necessary to first consider the history and the nature of lightning.

The history of lightning

Lightning fascinated and terrified man since the beginning of time. As primitive man did not understand the origin of the “fire from heaven” it was attributed to specific gods. Gods such as the Norse god, Thor, hurled lightning bolts and Zeus, the Greek god, and the Roman god Jupiter were thought to be in control of lightning. In Europe of the 18th century church bells were rung during a lightning storm with the belief that it would drive away the evil. The scientists of the day, on the other hand, promoted the practice as they thought that the acoustic vibrations would disrupt the lightning channel. During a time period of 33 years, 386 church steeples were hit by lightning and 103 bell ringers died. The 100 m high bell tower of St. Marks in Venice, Italy, was struck and destroyed by lightning three times between 1388 and 1762. After a lightning rod was fitted in 1766, no further incidents occurred. Gunpowder was also often stored in vaults beneath churches, leading to many explosions and fatalities when ignited by lightning. In one incident in 1856, 4000 people were killed when gunpowder ignited in the vaults of St. Jean on the Island Rhodes. Also in Africa, lightning is often seen as a punishment, that can be administered by certain persons, having mythical powers.

Benjamin Franklin experimented with the Leyden jar, the first capacitor, and noted the similarities between the discharges obtained and lightning. With the aid of his famous kite experiment, he proved this similarity in 1752. His other main contribution was the lightning rod that is used to intercept the lightning current and to divert it from the protected object.

The nature of lightning

Although the mechanism is not precisely known, it is generally accepted that negative charge builds up in at the base of the thundercloud with the upper parts having positive charge. Also, positive charge is induced on the earth, directly underneath the cloud. The base of the cloud is often at a height of 1 500 m and the overall height of the thundercloud could be as high as 12 000 m.

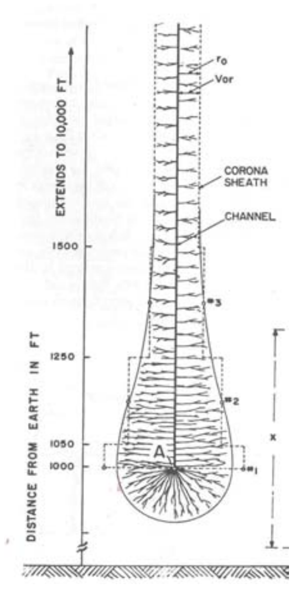


Fig. 5.8: Leader formation

Initiated by discharge activities in the cloud, air breakdown

commences in the direction of earth. Corona discharges commence at the cloud base and develop into a stepped leader as is shown in Fig. 5.8. The leader consists of a highly conductive, ionized channel and a sheath of corona that surrounds it. The diameter of the channel is about 2 mm and the voltage gradient along its length is 50 kV/m and a typical potential of the leader is 50 kV. The leader develops in a zigzag step-wise fashion, driven by the corona at its tip, in steps of about 50 m length. The leader is not visible to the naked eye and its current is of the order of 100 A.

The conductive leader can be seen as an extension of the charge at the cloud base and has a negative charge. As the leader approaches ground, positive charges are induced at the earth surface and on conductive objects that protrude above the earth surface. As is shown in the sequence of diagrams in Fig. 5.9, corona appears at the tip of a tower on the earth surface, leading to eventual neutralisation of the negative charge on the leader by the upward flowing positive charge (the return stroke). The upward return stroke is highly visible and is associated with a current as high as 200 kA, with a median value of 35 kA.

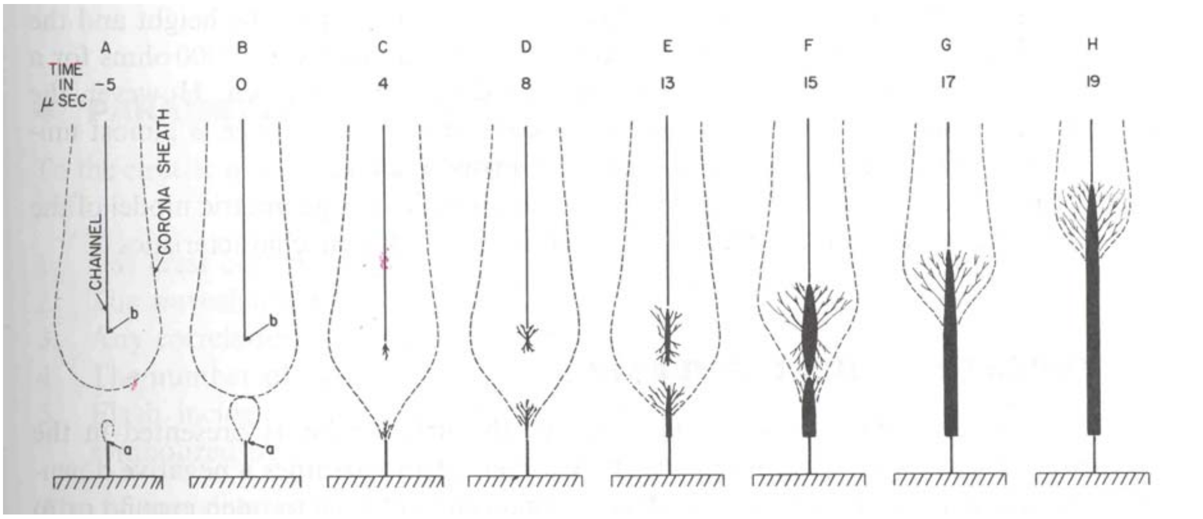


Fig. 5.9: Leader approaching ground

The temperature of the return stroke exceeds 30 000 °C. The point where the corona envelopes meet (stage B in Fig. 5.9) is the "point of discrimination" where "it has been decided" that the lightning will hit the tower. The distance between the top of the tower and the tip of the leader is known as the *striking distance*.

The process of stepped leader development up to the return stroke is summarised in Fig. 5.10.

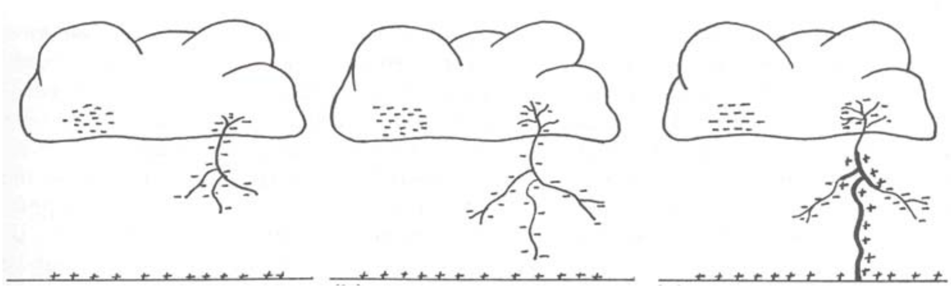


Fig. 5.10: Stages in the development of lightning.

A photograph that was taken by moving the image sideways (using a rotating mirror) during the lightning process is shown in Fig. 5.11. The total duration of the photograph was about 2 ms and the vertical height is about 400 m.

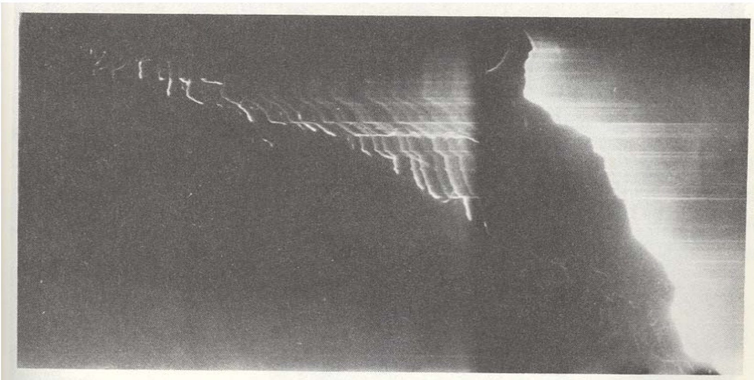


Fig. 5.11: Streak photograph of lightning development

Subsequent to the first stroke, multiple follow-up strokes are possible when other charge centres in the cloud connect with the already ionized path of the lightning. The current peaks of these strokes are lower, but they are steeper.

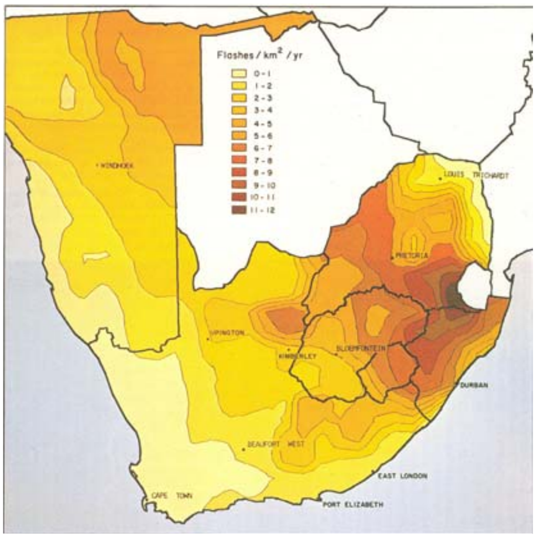


Fig. 5.12: Ground flash density map for South Africa.

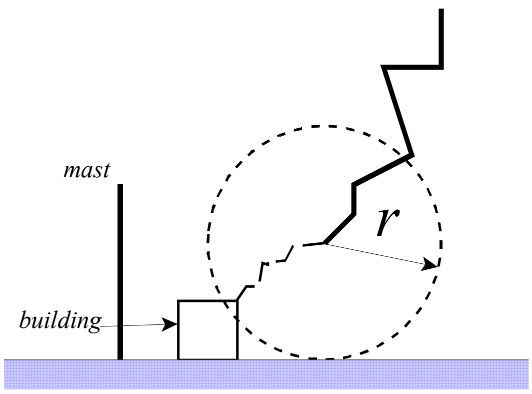


Fig. 5.13: Striking distance: the rolling sphere concept

Lightning is described in terms of its main parameters: the crest current, the wave shape of the current, the number of strokes per flash and the ground flash density, N_g, in flashes per square km-year. Maps have been compiled for N_g and a typical one for South Africa is shown in Fig. 5.12. Typical values are values of N_g are:
Johannesburg = 6.5, Bloemfontein = 5.0, Cape Town = 0.3 and Durban = 5.0 flashes per square km-year.

Protection against lightning

As the stepped leader approaches earth, positive leaders reach up from close-by sharp conducting objects. Once the distance between the leader and the object reaches a certain value, the striking distance, r, flashover takes place to the nearest object. The effect of the striking distance can be simulated by visualizing a sphere with radius r and centre point at the tip of the leader descending together with the leader. The earthed object first touched by the sphere is struck by the lightning. This is shown in Fig. 5.13.

The radius of the sphere is a function with the charge available in the leader. The discharge current is proportional to this charge, with the result that typical radii can be associated with the expected magnitude of the lightning current. For example [Kreuger]:

I = 10 kA $\quad r$ = 40 m

I = 50 kA $\quad r$ = 130 m.

In the case of a lightning protection mast (or air terminal), the effect of the rolling sphere may be approximated by a cone as shown in Fig. 5.14. Structures inside the cone will be protected by the mast.

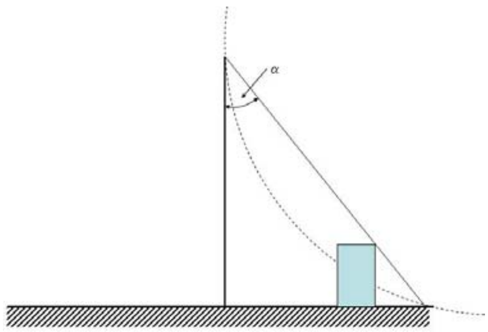


Fig. 5.14: Protection cone

In the case of high voltage overhead lines, an overhead earth (screen) wire may be provided to intercept the leader. In Fig. 5.15 the shaded area represents the vulnerable area from which the leader tip will strike the phase conductor rather than the ground surface or the earth wire. The application of two overhead ground wires to a HV line is shown in Fig. 5.16.

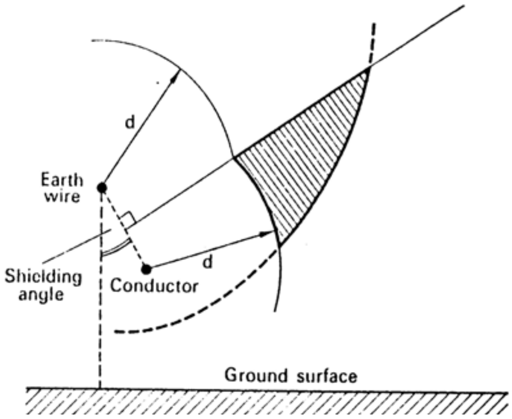


Fig. 5.15: Optimal placing of earth wire minimise vulnerable area

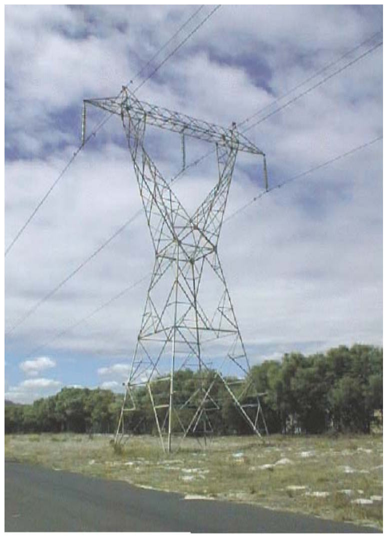


Fig. 5.16: High voltage line with two overhead screen wires

Based on this approach, shielding angles of 30° have been used successfully for towers with heights up to 24 m. Higher towers experienced a poor lightning performance. Further research led to a geometrical model, incorporating the concept of the attractive radius of a conductor.

The attractive radius is a concept, similar (identical) to the striking distance of the lightning leader. The attractive radius is given by:

$$R_A = 0.84\, I^{0.74}\, h^{0.6} \tag{5.5}$$

with h the height of the structure in m and I the current in kA. For a median current of I = 35 kA:

$$R_A = 14\, h^{0.6} \tag{5.6}$$

The application of the attractive radius concept is illustrated in Fig. 5.17, where the attractive radii of the shield wires and the phase conductors (r_c) are shown together with the striking distance to ground (r_g). The vulnerable area for vertically approaching leaders is D_c. Based on this approach, the shielding angle for a 46 m high 345 kV double circuit line has to be 12° [Hileman]. In general, higher structures require smaller shielding angles.

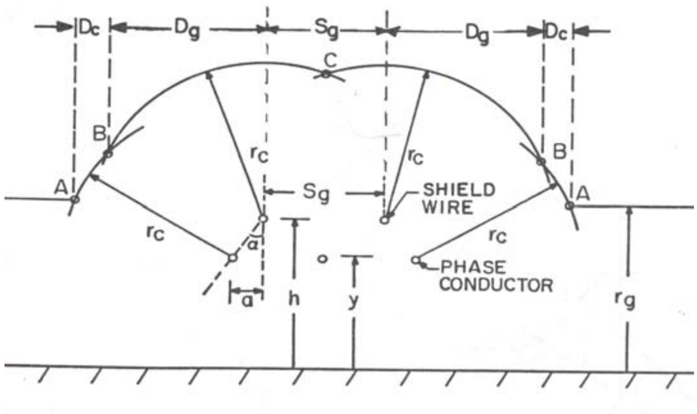


Fig. 5. 17: The geometrical model for line lightning protection.

Overvoltages caused by a direct stroke (a shielding failure)

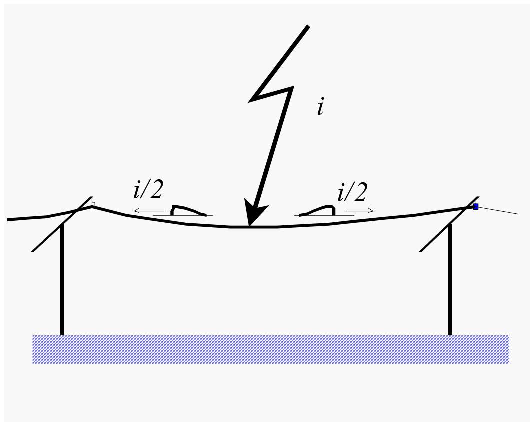


Fig. 5.18: Direct lightning stroke to a line

If an overhead power or telephone line is struck, the lightning surge current initiates two travelling current waves proceeding along the line in two directions as is shown in Fig. 5.18 at the speed of light. There are two voltage waves associated with the current waves with peak values:

$$v = \frac{1}{2} i \, Z_c \qquad (5.7)$$

where: i: peak current (A)

v: peak voltage (V)

Characteristic impedance of line $Z_c = \sqrt{\dfrac{L}{C}}$ (5.8)

Consider the case where Z_c=350 ohm and i = 10 kA when a voltage v = 1,75 MV appears on the line. Such a high voltage would cause immediate breakdown of the air, surrounding the line, causing power frequency fault current to flow to earth.

In cases where the air does not break down immediately, the travelling voltage waves are propagated along the lines and are somewhat attenuated by the increased corona on the wires (the steepness of the surge is reduced). The insulation of equipment directly connected to the line, such as transformers, can be damaged by these surges. For this reason the insulation transmission and distribution equipment are also specified and tested in terms of impulse voltages. Surge diverters (lightning arresters) are also provided at the substations to limit the overvoltages.

Indirect stroke (induced voltages)

Consider the case where lightning strikes an object such as a tree as shown in Fig. 5.19. The lightning current injected into the ground causes a potential rise near the electrode. This causes the so-called step potential. The structure (the tree) also has a surge impedance, causing the so-called touch potential. The importance of a low earthing impedance for the object or air termination is obvious. The factors affecting the earthing resistance have been dealt with in Chapter 2. As the lightning current contains a high frequency component, the inductance of the tower and the grounding electrode also plays an important role.

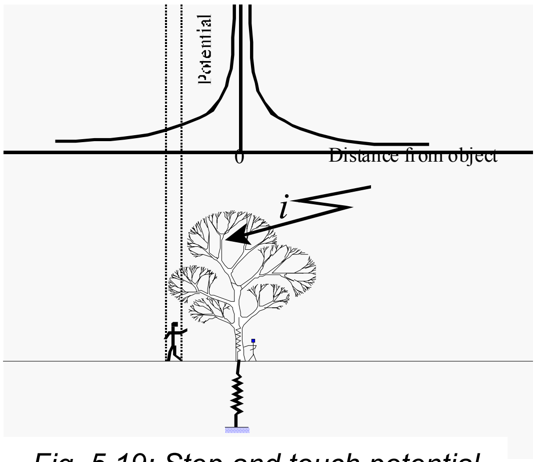


Fig. 5.19: Step and touch potential due to lightning.

From an overvoltage point of view, indirect strokes cause travelling waves on power lines as is shown in Fig. 5.20. The negative charge on the cloud and the approaching leader induces positive charge on the line. When the cloud discharges to another object, the charge on the line is released and it travels along the line. The associated voltage wave may damage transformer insulation. The magnetic field associated with the lightning current may also induce voltages in loops formed by low voltage or communications lines.

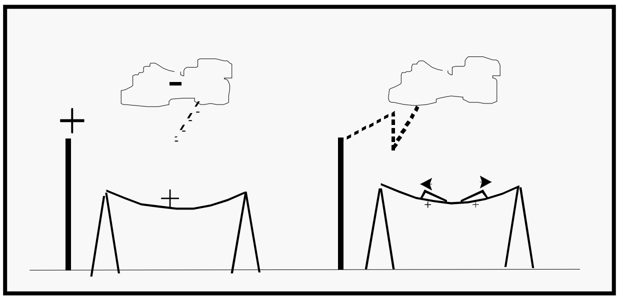


Fig. 5.20: Induced overvoltages due to nearby lightning stroke

Ground potential rises: back-flashover

A lightning stroke to the tower or the earth wire may cause a potential rise of the tower, due to the tower impedance and the tower footing resistance, as appears from Fig. 5.21. If the tower impedance is high the potential of the tower will exceed the insulation level of medium voltage lines, resulting in a flashover from the tower to the line. From this section it is clear that the frequency of occurrence and magnitude of lightning overvoltages can be controlled by proper shielding and grounding with a low grounding resistance.

Fig. 5.21: Back flashover to tower due to stroke to tower of shielded line.

5.3 Surge Protection

If it is accepted that some overvoltage surges, due to either lightning or switching will occur on the transmission system, then steps must be taken to control the size of these surges.
In the case of switching surges, the magnitudes could be controlled by having circuit breakers that incorporate closing and tripping resistors and point on wave switching.
As shown before, the magnitude of lightning impulses is determined by the magnitude of the lightning discharge current. Proper shielding will minimize direct strokes and low tower footing resistances will reduce the incidence of back-flashovers. There is not much that can be done to control the incidence of indirectly induced overvoltages due to lightning.

Once all these steps have been taken, the use of surge arresters facilitates the protection of vulnerable apparatus against harmful overvoltages. As explained in section 5.1.1, standard insulation levels can also be defined, based on the protection levels of the surge diverters.

There are various types of overvoltage controlling devices:

Protective gaps: These take the form of rod or horn gaps across insulators or transformer bushings. These gaps provide poor protection for short, high impulses. In addition, operation of such a gap results in a earth fault on the power system and has to be cleared by the protection relays.

Silicon carbide gapped arresters: A non linear SiC resistors that can pass high current pulses of short duration while maintaining its terminal voltage at a low level. The series arc gaps extinguish the 50 Hz follow current. Magnetic blow-out coils are used to help to interrupt the 50 Hz current.

Gapless ZnO arresters: Metal oxides are non linear over an extensive range of current densities and can therefore be used without series gaps. The ZnO devices have superior characteristics and are nowadays preferred, especially to protect transformers against steep impulses. Fig. 5.22 shows how the same wave is limited by the three different devices [Kreuger]. In Fig. 5.23 the three devices are used to protect a transformer.

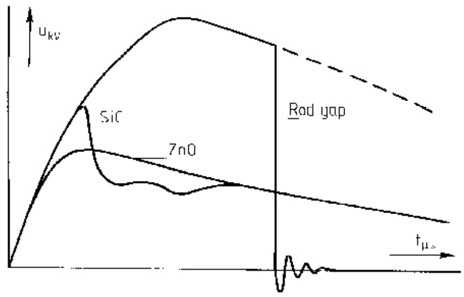


Fig. 5.22: Limiting an impulse with three protective devices [Kreuger]

It is important that protective devices be placed as near as possible to the equipment requiring protection. If this is not done, reflection at the transformer causes doubling of the voltage, thus making the device less effective. The phenomenon may also be explained in terms of a lumped parameter model by noting that the Ldi/dt voltage drop is added to the protective level of the arrester.

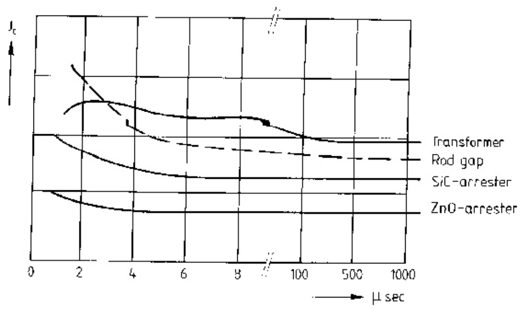


Fig. 5.23: Voltage-time curves od 3 devices, used to protect a transformer [Kreuger]

It is advisable that the surge arresters be placed as close as possible to the protected transformer, as voltage doubling takes place at the transformer. Considering an incoming impulse wave with a linear steepness, S kV/μs, the maximum distance that the arrester may be placed from the transformer is given by:

$$D = 2(V_{IL} - V_{SA})\, c / S \qquad (5.9)$$

with D: length of conductor between transformer and arrester, including connections and downleads.

V_{IL}: Impulse level (kV)

V_{SA}: Protection level of the surge arrester.

c: Wave speed (speed of light), 300 m/μs

5.4 Coordinated woodpole insulation coordination

A basic insulation level is chosen for the equipment at each voltage level. The BIL for 11 kV equipment is typically 95 kV. In areas of high lightning incidence, it has been shown to be feasible to raise the impulse level to 200 kV by including a portion of the wood pole in the path to ground, in series with the insulator. Although not earthed directly, the metal ware on the insulators should be bonded to prevent ignition of the wooden cross-arms due to pollution leakage current to ground.

5.5 Specifications

Flashover voltages are specified in specifications such as SABS 1019. The durations of the expected overvoltages are given in Fig. 5.24.

The strengths of the different types of insulation are given, superimposed on the data of Fig. 5.24 in Fig. 5.25. In this figure, the following insulation classes are defined:

Class I: Small Air, SF6 gaps;

Class II: Large air gaps, as used in HV transmission systems

Class III: Liquids, solids

It will be noted that Class II shows a minimum, exactly coinciding with switching impulses. For this reason the specifications for equipment for > 300 kV (Range C in SABS 1019) also include a switching impulse test.

The specifications are given on the following pages.

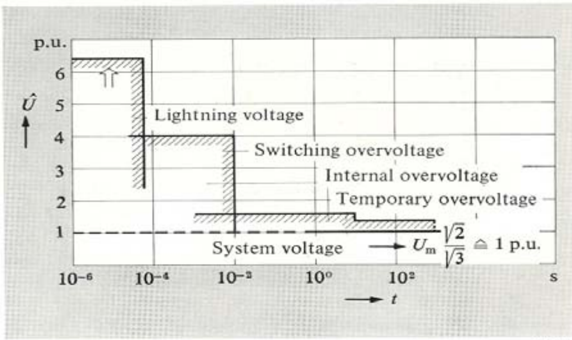


Fig. 5.24: Durations of the various types of overvoltage

Fig. 3 – Typical withstand voltage of various insulating media

a = Surge withstand values
b = Power-frequency withstand value
/////// = Overvoltage range
A = Lightning overvoltage
B = Switching overvoltage
C = Temporary overvoltage
I, II, III = Typical insulation classes
* IEC test voltages

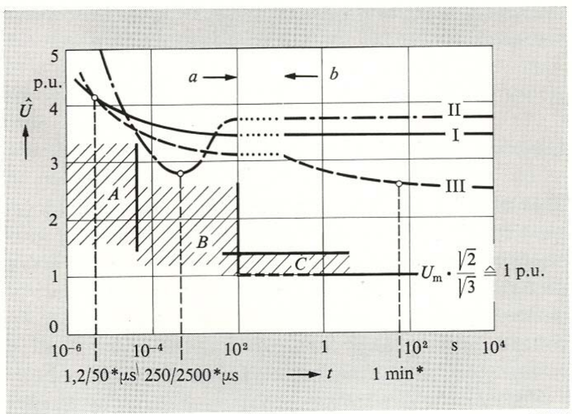


Fig. 5.25: Withstand characteristics of the various insulation classes, together with the overvoltage durations

Range A: 1 kV < U_m < 52 kV
Range B: 52 kV ≤ U_m < 300 kV
Range C: 300 kV ≤ U_m

5.4 STANDARD VOLTAGES AND INSULATION LEVELS IN RANGE A

NOTE: See C-4.1 for long duration power-frequency tests to determine aging of internal insulation or performance of external insulation under polluted conditions.

5.4.1 General. The standard highest voltage for equipment U_m and nominal system voltage U_n shall be of the appropriate combination of values given in Columns 1 and 2 of Table 2.

TABLE 2 - STANDARD VOLTAGES AND INSULATION LEVELS FOR RANGE A

1	2	3	4	5	6
Highest voltage for equipment U_m, r.m.s., kV	Nominal system voltage U_n, r.m.s., kV	Rated lightning impulse withstand voltage, peak, kV		Rated short duration power-frequency withstand voltage, r.m.s., kV	
		List 2	List 3	List 2	List 3
*2,4	2,2	40	40	10	12
3,6	3,3	40	45	10	16
7,2	6,6	60	75	20	22
12	11	75	95	28	28
24	22	125	150	50	50
36	33	170	200	70	70

*Not a preferred value for use in South Africa. This value is not listed in IEC Publication 71-1.

5.6.1 <u>General</u>. The standard highest voltage for equipment U_m and nominal system voltage U_n shall be the appropriate combination of values given in Columns 1 and 2 of Table 4.

TABLE 4 - STANDARD VOLTAGES AND INSULATION LEVELS FOR RANGE C

1	2	3	4	5	6	7	8
Highest voltage for equipment U_m, r.m.s., kV	Nominal system voltage U_n, r.m.s., kV	Base for p.u.* values, $U_m.\frac{\sqrt{2}}{\sqrt{3}}$, kV	Rated switching impulse withstand voltage, peak		Ratio between rated lightning and switching impulse withstand voltages	Rated lightning impulse withstand voltage, peak, kV	Rated short duration power-freqeuncy withstand voltage, r.m.s., kV
			p.u.*	kV			
300	275	245	3,47	850	1,24	1 050	460
362	330	296	3,21	950	1,37	1 300	570
420	400	343	3,06	1 050	1,36	1 425	630

*p.u. = per unit value of $U_m.\frac{\sqrt{2}}{\sqrt{3}}$, kV .

TABLE 3 - STANDARD VOLTAGES AND INSULATION LEVELS FOR RANGE B*

1	2	3	4	5	6
Highest voltage for equipment U_m, r.m.s., kV	Nominal system voltage U_n, r.m.s., kV	Base for p.u.+ values, $U_m \cdot \frac{\sqrt{2}}{\sqrt{3}}$, kV	Rated lightning impulse withstand voltage, peak		Rated short duration power-frequency withstand voltage, r.m.s., kV
			p.u.+	kV	
#52	44	42,5	5,88	250	95
72,5	66	59	5,93	350	140
100	88	82	4,63	380	150
			5,49	450	185
145	132	118	4,66	550	230
			5,50	650	275
245	220	200	4,25	850	360
			4,75	950	395

*Insulation levels for highest voltage for equipment $U_m < 100$ kV are based on an earth fault factor equal to $\sqrt{3}$ and for $U_m \geq 100$ kV, on an earth fault factor equal to $0,8\sqrt{3}$.

+p.u. = per unit value of $U_m \cdot \frac{\sqrt{2}}{\sqrt{3}}$, kV .

5.6 Review Questions

1. In Fig. 5.3 $E=132/\sqrt{3}$, $L_{transformer}$ = 30 mH and C_{cable} = 50 μF. Check whether the Ferranti effect poses a problem.
   (Ans.: V_L=13.25 kV(-17%), V_0=89.45 kV (117%))

   (5)

2. Repeat example 5 .1, but consider the case where the current is chopped at 50% of the peak current value (I_{m1}). What is the frequency of the transient?
   (Hint: Read the derivation and use $0.5I_m$ as "chopped" current. At that moment both voltage and current are non-zero; energy is thus stored in both. The voltage peak occurs during the ensuing oscillation when the high frequency current goes through zero and all the energy is in the capacitor. This leads to the equation: $V_{m2}=\text{sqrt}(0.25*(L/C)*I_{m1}^2+ 0.75*V_{m1}^2)$)
   (Ans.: 16.27 V, frequency 62.8 kHz.)

   (5)

3. a) Explain the electro-geometrical model of lightning protection of a power line, with reference to Fig. 7.11
   b) Estimate the attractive radius of a 10 m high mast, if the expected lightning current is 40 kA.
   (Ans.: 51.3 m)

   (10)

4. Describe how a power line can flash over due to a direct stroke.
   A 400 kV line is hit directly by a 35 kA lightning bolt. The inductance of the line s 1.5 mH/km and the capacitance is 0.013 μF/km. Estimate the resulting overvoltage and discuss the expected performance of the line. Refer to the Insulation Levels given in this chapter.
   (Ans.: 5.94 MV)

   (10)

5. Explain how lightning can cause a flashover of a power line by the back flashover mechanism. How can this type of flashover be avoided?

   A tower on a 132 kV (U_m = 145kV) power line has a footing resistance of 10 ohm. The tower is struck by a 10 kA lightning bolt. Discuss the expected performance of the line, taking into account the lightning impulse withstand data given at the end of Ch. 5 of the notes.

   (10)

6. Describe the difference of construction and in performance of arcing horns, SiC and ZnO overvoltage protection devices.

   (10)

7. Explain why a switching impulse test is also required for systems with voltages of 275 kV and above.

   (5)

6 HIGH VOLTAGE SAFETY PRINCIPLES

Thomas Edison, who demonstrated the dangers of electricity with the electric chair …

Although any voltage above 40 volts can be lethal, extreme care is required when working in a high voltage environment. Every object should be treated with respect and should only be touched when a reliable visible earth connection is confirmed. There should be adhered to the relevant safety regulations.

The high voltage environment is hazardous owing to the following possible phenomena:

a) capacitive and inductive coupling
b) air insulation breakdown when too close to a high voltage conductor
c) leakage current along an insulating stick that is polluted/ damp
d) earth potential rise due to high transient (lightning) or fault current: step and touch potentials.

6.1 Judiciary Aspects

Every country has its own safety regulations. In South Africa, the aims of the Occupational Health and Safety Act, 1993 is as follows:

To provide for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery; the protection of persons other than persons at work against hazards to health and safety arising out of or in connection with the activities of persons at work; to establish an advisory council for occupational health and safety; and to provide for matters connected therewith.
(http://www.acts.co.za/ohs/index.htm)

Furthermore, the South African Electricity Act (Act 41 of 1978) regulates specific aspects relating to the generation, transmission and distribution of electricity. One clause that is of relevant is the following:

“Liability of undertaker for damage or injury:

In any civil proceedings against an undertaker arising out of damage or injury caused by induction or electrolysis or in any other manner by means of electricity generated or transmitted or by leaking from the plant or machinery of any undertaker, such damage or injury shall be presumed to have been caused by the negligence of the undertaker, unless the contrary is proved.”

6.1.1 Effect of electrical currents on the human body

An American, Charles Dalziel, did some basic research and, on the basis of his work, Table 6.1 has been compiled.

Table 6.1: The effect of electric currents on the human body

Current range (mA)	Effect
1	Threshold of perception
1 - 6	Let-go currents
6 - 25	Painful, difficult to release energized objects
25 - 60	Muscular contractions, breathing difficult
60 - 100	Ventricular fibrillation

The resistance of the human body is generally assumed to be of the order of 1000 ohms. This implies that, even at a voltage of 60 volts, electric shock can have serious consequences.

In his research, Dalziel established the following formula for the maximum “safe” body current, I, for humans:

$$I = \frac{0.116}{\sqrt{t}} \tag{6.1}$$

with I: current in Ampere

t: time duration in seconds of the current flow

Eq. (6.1) is used in the design of ground electrodes and earth grids of substations to limit step and touch potentials to safe limits.

The basic danger of electricity is electrocution and particularly, ventricular fibrillation, which is a condition in which disordered electrical activity causes the lower chambers of the heart, ("ventricles"), to contract chaotically.

In the case of high-voltage (> 500 to 1000 V), internal burns can also occur. The majority of fatalities due to high voltage is due to arc-flash burning. This happens for example when a manually operated circuit breaker faults and the operator is injured by burning by the high temperature of the arc.

First aid is best administered by trained persons, a usual technique being CPR, as shown in Fig. 6.1.

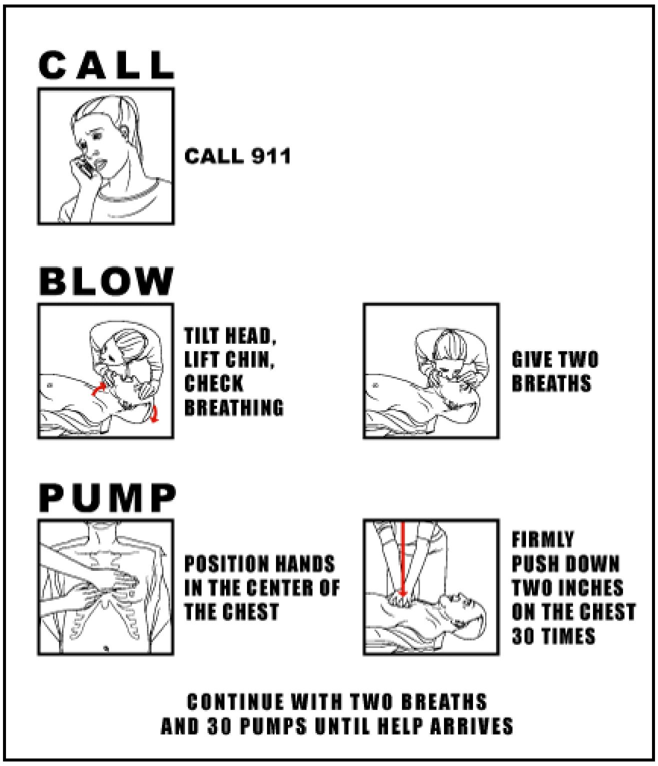


Fig. 6.1: First aid for a victim of electric shock.

6.1.2 Electrical clearances

The safe electrical clearances from the Occupational Health and Safety Act are given in Table 6.2. These clearances have no relation to the actual flashover or withstand distances of the actual voltages, but allow, from experience, for the safe movement of vehicles, etc. One typical type of accident is when a mobile crane drives into an overhead high voltage line. In such cases, the first point to be checked is whether the height of the line complies with the Act. The sag of a power line is temperature dependant, and designs should allow for a worst case scenario (50 °C).

Table 6.2: Electrical clearances

Max voltage for which insulation is designed kV r.m.s phase to phase cradles.	Minimum safety clearance	Minimum clearance in metres				
		Above ground outside townships	Above ground in townships	Above roads, railways, tramways	To communication lines, power lines,	To buildings & structures not part of power lines.
1.1 or less	-	4.9	5.5	6.1	0.6	3.0
7.2	0.15	5.0	5.5	6.2	0.7	3.0
12	0.20	5.1	5.5	6.3	0.8	3.0
24	0.32	5.2	5.5	6.4	0.9	3.0
36	0.43	5.3	5.5	6.5	1.0	3.0
48	0.54	5.4	5.5	6.6	1.1	3.0
72	0.77	5.7	5.7	6.9	1.4	3.2
100	1.00	5.9	5.9	7.1	1.6	3.4
145	1.45	6.3	6.3	7.5	2.0	3.8
245	1.85	6.7	6.7	7.9	2.4	4.2
300	2.35	7.2	7.2	8.4	2.9	4.7
362	2.90	7.8	7.8	9.0	3.5	5.3
420	3.20	8.1	8.1	9.3	3.8	5.6
800	5.50	10.4	10.4	11.6	6.1	8.5
533 kV d.c.*	3.70	8.6	8.6	9.8	4.3	6.1

* Maximum voltage to earth for which insulation is designed.

Provided that these figures are base on the assumption that clearances shall be determined for a minimum conductor temperature of 50°C and a swing angle corresponding to wind pressure of 500 Pa: Provided further that where under normal conditions power line conductors operate at a temperature above 50°C, the clearance at the higher temperature at which the conductors operate shall be in accordance with the clearance indicated in the table;

b. the clearances of conductors and other wires over the normal high-water level of power lines crossing over water to be not less than the values for power lines above the ground outside townships: Provided that if the owner of the land on which the water is situated requires a greater clearance and no agreement can be reached, the dispute shall be referred to the chief inspector for a decision; and

c. the distance of any power line from an explosives magazine to comply with the requirements of the Explosives Act, 1956 (Act 26 of 1956).

c. No person shall construct any road, railway, tramway, communication line, other power line, building or structure or place any material or soil under or in the vicinity of a power line which will encroach on the appropriate minimum clearances prescribed in terms of subregulation (1).

3. No person shall encroach in person or with objects on the minimum safety clearances prescribed in subregulation (1) or require or permit any other person to do so except by permission of the supplier or user operating the power line.

4. The supplier or user, of power lines shall control vegetation in order to prevent it from encroaching on the minimum safety clearance of the power lines and the owner of the vegetation shall permit such control.

6.1.3 Safety signs and working procedures

Signs of the type shown in Fig. 6.3 should identify high voltage equipment. Other types of signs indicate work in progress, etc.

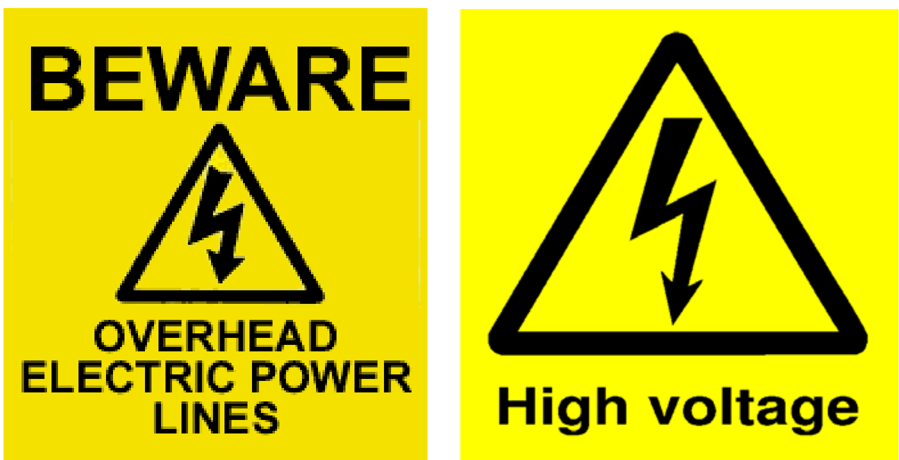


Fig. 6.3: Typical standard high voltage warning signs

6.2 Capacitive and Inductive Coupling, Floating Objects, Current Loops

Where, as shown in Fig. 6.4, a conductor such as d finds itself near a three phase line, there exists the possibility of capacitive and magnetic induction as explained in section 2.1.5 and 2.2.1.

This example is particularly relevant where maintenance is being done on a line that, for a distance, runs parallel to an energized high voltage line.

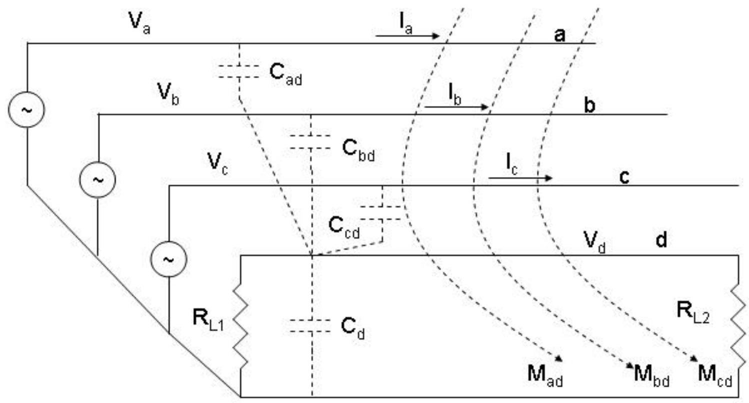


Fig. 6.4: Electromagnetic induction

When working under such circumstances, safety can be ensured by adhering to the rules and regulations, especially those that concern earthing.

6.3 Safety Earthing

As pointed out in section 2.3, an earth electrode has a certain resistance. When current flows down a connection to ground, the potential of the conductor rises. The implication of this is shown in Fig. 6.5, where a two-conductor supply line is earthed at the point where maintenance is being done. It will be noted that the potential difference between the two conductors is only zero at the point where the earthing connections are fitted. Further away, the potential difference increases.

6.3.1 Working earths

While working on a line, a worker must be sure that he is safe. Although the supply to a line is off, voltage could still be induced in the line due to capacitive or magnetic induction as explained in sections 2.1.5 and 2.2.1. Consider the two cases shown in Fig. 6.6. If

someone would inadvertently switch on the full supply voltage of 10 000 V, a current of I=10 000/2 = 5 000 A would flow to ground via the earth conductor. This will apply in both cases. Where the pole is not connected to the ground conductor (Fig. 6.6(a)), a current I = 10 000/ 100 000 = 0.1 A (100 mA) would flow through the worker with possible lethal consequences.

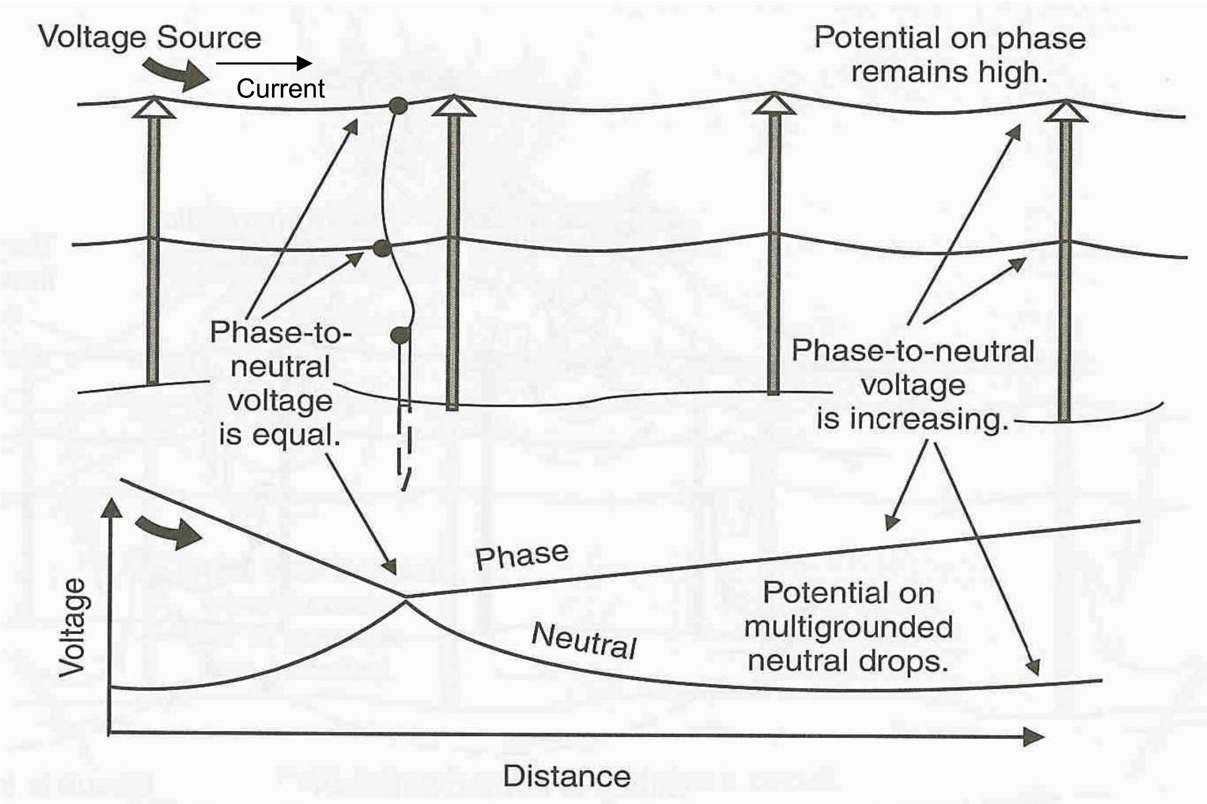


Fig. 6.5: Safety earth on a two-wire line.

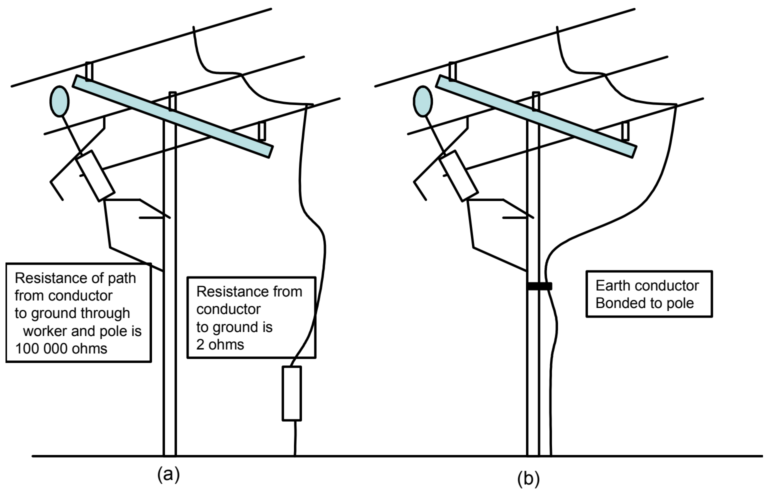


Fig. 6.6: Unsafe (a) and safe (b) earthing practices for work on a line.

In Fig 6.6 (b), where the earth conductor is connected to the pole, the worker is in effect in parallel with the upper section of the low resistance earth conductor, placing the worker effectively in an equipotential zone.

The safe practice for three phase lines is shown in Fig. 6.6, where a cluster earth system is used. This method ensures that the voltage on both sides of the worker and to ground is the same, i.e. the worker is in an equipotential space or a Faraday cage.

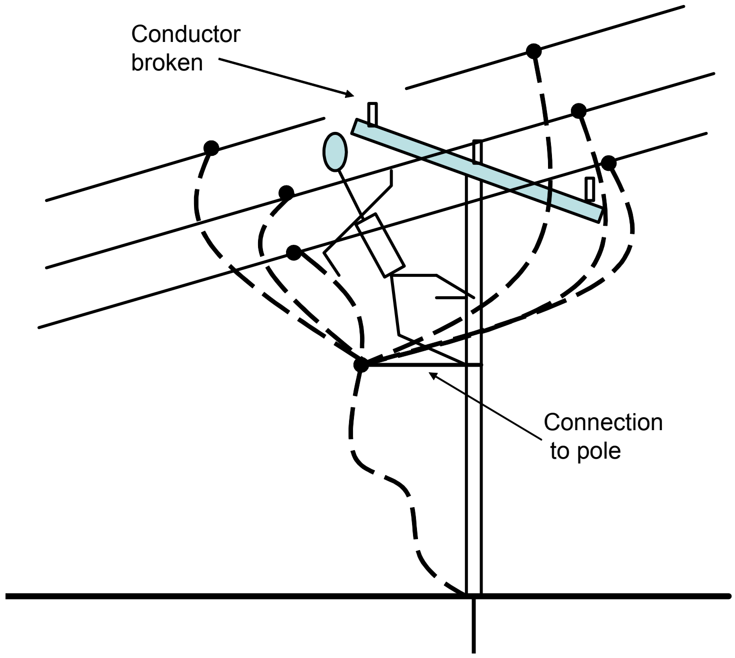


Fig. 6.7: A cluster earth

6.4 Step and Touch Potential, Equipotential Platforms and Voltage Transfer

The earthing resistance of an electrode was discussed in section 2.3 and in section 5.2.3(e), the concepts touch and step potentials were explained in connection with lightning. These concepts are also valid in the case of power frequency earth currents and earth fault currents in particular. The potential at the ground surface in the vicinity of an earth electrode will be raised when a large current flows into ground.

Earth mats, consisting of a square mesh of interconnected copper bars, are therefore used in substations. All transformer neutral points and all metal structures are solidly connected to the mat. Apart from assisting in lowering the earthing impedance, the mat also provides an equipotential platform to limit step and touch potentials.

Another hazard, relating to earthing, is illustrated in Fig. 6.8. If a connection (mains connection, telephone line, etc.) is made between a remote earth that experience a voltage increase due to, say, a lightning discharge, that voltage may be transferred to the vicinity of a local earth that is at zero potential. This can cause fatalities and damage of equipment. The solution is to bond earths where possible or to use overvoltage protection devices, such as metal oxide varistors and/or gas discharge tubes.

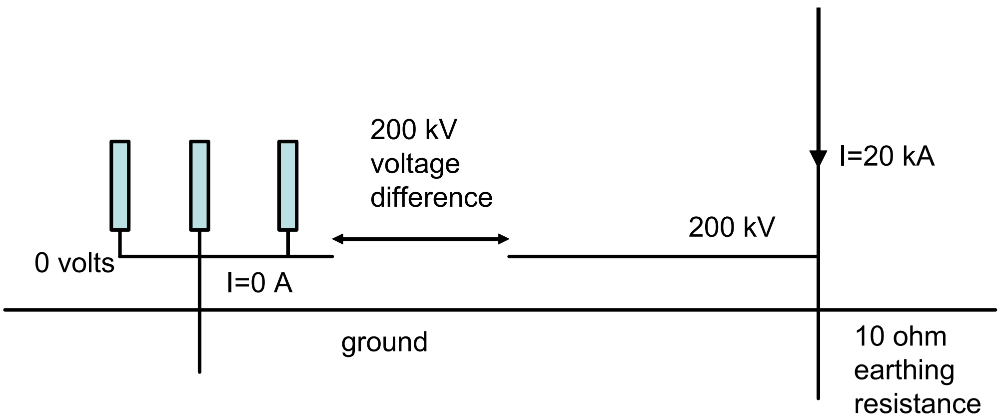


Fig. 6.8: Voltage transfer

6.5 Safety in the High Voltage Laboratory

When working with high voltage in the laboratory, very strict rules apply:

- Sufficient clearances should be provided to prevent unplanned flashovers.
- Suitable barriers should be provided.
- A suitable earth plane should be provided as safety earth and reference point for measurements. It is not advisable to try to separate earths. In measuring circuits, such as voltage dividers and the Schering bridge, a bolted connection to earth is required. If this connection is broken, the full voltage appears across the break. Protective spark gaps and overvoltage limiting devices can be used.
- Any object in the laboratory should be either well connected to earth potential or at high voltage. "Floating" objects cause problems.
- Suitable interlocks that switch off the power on opening should be provided on doors and gates leading to live areas.
- A suitable earth stick should be provided to earth any piece of equipment before touching. The rule is not to become part of a circuit. Special care should be taken with circuits having capacitors – especially with DC.
- A person should never work alone in a high voltage laboratory: double check and cross-check.

6.6 Review Questions

1. a) Explain the concepts: step and touch potential.

(5)

   b) Comment on the relative safety of the practices followed by the workers in Fig. 6.6 and Fig. 6.7.

(5)

2. Explain voltage transfer.

(5)

3. What are the dangers of working on a line that runs parallel to an energized line?

(5)

4. What is an earthing impedance? Explain all the advantages of a low earthing impedance?

(10)

5. Explain the purpose of the documents relating to the following (consult the Internet):

a) The Electricity Act

c) OSH Act

Practical High Voltage Engineering 2006*(draft)*

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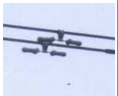
Test

Chapter 1: Introduction

Mark the valid statements with a tick mark (more than one statement may be valid).

	Statement	A	B	C
1	HVDC Lines: (A) are used over long distances, (B) are good from a power system stability point of view, (C) are useful to supply power to consumers en route.			
2	The main advantage of AC is (A) that transformers can be used, (B) reactive power can be used (C) power and voltage stability can be addressed.			
3	A higher transmission voltage (A) results in a higher current in the transmission line, thus transferring more power (B) a higher current resulting in a lower voltage drop along the line (C) a lower current and a lower voltage drop along the line.			
4	The purpose objects shown are (A) to scare birds away (B) to prevent corona (C) to damp conductor vibrations 			
5	The purpose of grading foils in a capacitor bushing is (A) to cause an uniform voltage distribution in the axial direction (B) to cause an uniform voltage distribution in the radial direction (C) to prevent internal partial discharges.			
6	SF6 gas is used in circuit breakers (A) due to the arc quenching properties of the gas (B) due to the insulating properties of the gas (C) due to the cooling properties of the gas			
7	The oil in an oil circuit breaker is used (A) due to the arc quenching properties of the oil (B) due to the insulating properties of the oil (C) due to the cooling properties of the oil.			
8	The oil in a transformer is used (A) due to the arc quenching properties of the oil (B) due to the insulating properties of the oil (C) due to the cooling properties of the oil.			
9	The arc in a vacuum circuit breaker (A) is maintained by the metal vapour of the contacts (B) is maintained by gas ions (C) is interrupted when the vapour condenses.			
10	The main purpose of an isolator is (A) to interrupt current (B) to disconnect the circuit under no load (C) to connect a circuit under no load conditions.			
11	The main purpose of grading rings on lightning arresters is (A) to prevent corona (B) to ensure a uniform distribution over the height of the arrester (C) to provide lightning protection			

Test
Chapter 2: Fields

Mark the valid statements with a tick mark (more than one statement may be valid – if so, mark the order of importance by using a ”1” , a “2” or a “3”).

	Statement	A	B	C
1	The lowest flashover voltage is obtained for a 20 mm gap in the case of (A) a uniform gap (B) a sphere gap or (C) a gap between two cylinders, having the same radius as the spheres.			
2	A 10 mm radius sphere is far removed from other objects. It is connected to an ac high voltage source. The r.m.s. voltage where discharges begin is (air breaks down at 3 kV/mm): (A): 60 kV, (B): 30 kV, (C): 21.2 kV			
3	The outside radius of a co-axial tubular busbar system is fixed at 100 mm. The highest r.m.s voltage that can be transmitted over the line with a maximum field strength not exceeding 2 kV/mm is: (A) 52 kV, (B) 73.6 kV, (C) 38 kV.			
4	The main purpose of bundle conductors is (A) to facilitate cooling of the conductors, (B) to lower the surface field strength of the conductors, (B) to avoid the effects of skin effect.			
5	The electric field strength in a spherical air void in a solid dielectric with ε_r=4 is (A) 8/5, (B) 12/9 or (C) 4 times as high as that in the solid.			
6	The value of the capacitively induced voltage on a parallel “floating” line does not depend on the length of the object. (A) True (B) False			
7	The value of the current, when touching a “floating” object does not depend on the length of the line. (A) True (B) False			
8	The length of a vertical 20 mm diameter rod to obtain a 10 ohm earthing resistance in soli with a 100 ohm metre resistivity is (A) 1.2 m, (B) 5.3 m, (C) 13.7 m.			
9	The electric field of a 533 kV line (eq. radius of conductor is 23 cm) at a height of 26 m is (A) 7.56 kV/m,(B) 75. 6 kV/m and (C) it complies with the occupational statutory limits*. (Use eq. 2.4a)			
10	The magnetic field, if the above conductor carries 1000 A is (A) 77 μT, (B) 7.7 μT and (C) it complies with the occupational statutory limits*.			

- The statutory limits on p. 43 of the notes apply to 50/60 Hz time varying fields, but can, with added safety, be used for DC.

Test
Chapter 3: Insulating Materials

Mark the valid statements with a tick mark (more than one statement may be valid – if so, mark the order of importance by using a ”1” , a “2” or a “3”).

	Statement	A	B	C
1	In an electric field, electrons move (A) slower, (B) faster, or (C) just as fast as positive gas ions.			
2	In an avalanche, one electron, starting at the cathode, multiplies to 1000 over a distance of 10 mm. The ionization coefficient (α) is (A) 690 (B) 6.9 or (C) 0.69 ionizations / mm.			
3	SF6 is a better insulating gas than air at the same pressure due to (A) its higher molecular weight (B) because it is more electronegative or (C) it is chemically inactive.	2		
4	An electronegative gas breakdown is likely when (A) $\alpha<\eta$, (B) $\alpha>\eta$ or (C) $\alpha=\eta$.			
5	The most likely flashover mechanism for a 1 metre long gap is (A) the Townsend mechanism (B) the streamer mechanism (C) the leader mechanism.			
6	The most likely flashover mechanism for a 50 mm long air gap under a pressure of 4 bar is (A) the Townsend mechanism (B) the streamer mechanism (C) the leader mechanism.			
7	In a circuit, using a high DC voltage it is advisable to use a voltage with a (A) positive (B) negative or (C) either polarity with respect to the grounded enclosure.			
8	The corona inception voltage of a 10 mm radius smooth conductor in a co-axial system with a 500 mm outside screen radius at standard atmospheric conditions is (A) 158.6 (B) 15.86 (C) 1.586 kV peak.			
9	Rain (A) increases (B) reduces (C) does not affect corona on power lines.			
10	The dielectric constant (permittivity) of an oil sample is obtained by (A) breakdown tests, (B) capacitance measurement (C) weighing the sample.			
11	A high value of tan δ indicates (A) a good insulation (B) poor insulation (C) nothing about the insulation quality.			
12	Dielectric losses are proportional to (A) voltage, (B) $(\text{voltage})^2$, (C) $(\text{voltage})^3$			
13	The thermal conductivity of damp soil is (A) higher, (B) lower, (C) the same as that of dry soil.			
14	Hard paper barriers are required in the oil between transformer windings to (A) channel oil flow, (B) provide additional insulation (C) to prevent failure			

	due to fibre bridge formation.			
15	In a non-uniform field fibres (A) move to the low field regions, (B) move to the high field regions (C) remain stationary.			
16	A 1 cm thick slab is placed in a 2 cm uniform gap to leave a 1 cm air gap. If the voltage across the electrodes is 20 kV, the field strength in the air gap is (A) 10 kv/cm. (B) 15 kV/cm, (B) 15 kV/cm.			
17	On a 66 kV line in a very heavily polluted area, allowing for a 10% overvoltage, one should use (A) 7, (B) 8 or (C) 9 glass discs (Given: creepage length 280 mm for one disc)			
18	The flashover voltage (line to neutral) of a 8 disc insulator string of above type under very heavy pollution of 25 μS is (A) 66.52 kV,(B) 60.33 kV, (C) 95.46 kV rms.			
19	The insulator string in (18) above is (A) suitable (B) not suitable for use on a 66 kV line under stated conditions.			
20	Atmospheric air is (A) a self-restoring (B) non-self-restoring insulating material.			

Test
Chapter 4: HV Testing

Mark the valid statements with a tick mark (more than one statement may be valid – if so, mark the order of importance by using a ”1” , a “2” or a “3”).

	Statement	A	B	C
1	Tests in the HV Lab are usually conducted (A) three phase, (B) single phase to ground, (C) phase to phase			
2	Half wave rectifiers are used in stead of full-wave rectifiers to (A) obtain a smaller ripple voltage, (B) to be able to use a ground reference plane, (C) for no reason.			
3	In the impulse generator shown in Fig. 4.8 the front time of the waveform is mainly determined by (A) R_1C_2, (B) R_2C_1, (C) R_1C_1			
4	If the charging voltage of a 2-stage impulse generator is 100 kV, an output voltage of (A) 95 kV, (B) 290 kV, (C) 190 kV is likely.			
5	Two diodes in series are used in a half-wave rectifier charging circuit (to handle the peak current, (B) to handle the peak forward bias voltage, (C) to handle the peak reverse bias voltage.			
6	Capacitive dividers can be used for the measurement of (A) DC, AC and impulse voltages, (B) AC voltages only, (C) AC and impulse voltages.			
7	The peak voltage / $\sqrt{2}$ is used to indicate the AC flashover voltage as (A) it is the rms voltage, (B) flashover occurs at the voltage peak, (C) flashover depends on the rms voltage.			
8	The Schering bridge is used th measure (A) the capacitance and tan δ, (B) the capacitance only, (C) tan δ only.			
9	A tan δ value of 2 % is (A) acceptable, (B) not acceptable, (C) marginally acceptable for a 400 kV bushing.			
10	Partial discharges associated with an internal void in insulation occurs (A) near the voltage peak, (B) near the current peak, (C) in the vicinity of the voltage zero crossings.			

Test

Chapter 5: Overvoltages and Insulation Coordination

Mark the valid statements with a tick mark (more than one statement may be valid – if so, mark the order of importance by using a ”1” , a “2” or a “3”).

	Statement	A	B	C
1	Insulation coordination is defined as the correlation of the insulation of the electrical equipment with the (A) overvoltages, (B) protective devices, (C) air density, such that the insulation is protected from excessive overvoltages.			
2	Switching overvoltages are of importance (A) at all voltage levels, (B) voltage levels above 100 kV, (C) voltage levels above 300 kV.			
3	The typical duration of an overvoltage due to lightning is (A) 50 s, (B) 10 ms, (C) 100 μs.			
4	In a system with $X_0/X_1=10$, the overvoltage factor due to earth faults is (A) 3, (B) 2, (C) 1.5.			
5	The maximum switching overvoltage due to fault current is (A) V_m, (B) $2V_m$, (C) $3V_m$.			
6	The typical diameter of the conductive leader, associated with lightning is (A) 0.5 m, (B) 2 mm, (C) 10 mm.			
7	The most common type of lightning overvoltage causing outages on unshieded 11/22 kV lines is (A) due to direct strike, (B) indirect (induced) (C) back-flashover.			
8	Co-ordinated wood-pole insulation is used on (A) shielded lines, (B) unshielded lines, (C) both types.			
9	The best remedy against back-flashover is (A) better shielding, (B) increase the tower footing resistance, (C) lower the tower footing resistance			
10	The most effective type of surge suppressor is (A) rod gap, (B) Si Carbide gapped arrester, (C) gapless ZnO arrester			

Test
Chapter 6: Safety

Mark the valid statements with a tick mark (more than one statement may be valid).

	Statement	A	B	C
1	Before touching a HV object (A) disconnect, (B) earth, (C) first disconnect then earth.			
2	According to Dalziel, the maximum "safe" current that a person can withstand for 4 seconds is (A) 0.116 A, (B) 0.058 A, (C) 0.58 A			
3	CPR involves (A) 1 breath and 10 pumps, (B) 2 breaths and 20 pumps, (C) 2 breaths and 30 pumps, repeatedly until help arrives.			
4	The minimum electric clearance of a 66 (72) kV line above a road is (A) 3.2 m, (B) 5.7 m, (C) 6.9 m.			
5	The correct type of working earth consist of (A) at least one connection to earth, (B) two connections to earth, one on each side, close to the worker, (C) connections to earth, at each end of the relevant line section.			
6	Before touching an object in the HV Lab, (A) voltage should be switched off, (B) voltage should be switched off and a visible earth stick is to be connected, (C) rubber gloves should be worn.			

HIGH VOLTAGE LABORATORY PRACTICAL

Part 1: DC and AC Flashover and Corona

SAFETY MEASURES:
• *Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors).*   • *A copper sheet serves as the ground reference. This sheet is connected to ground. It is important to ensure good connections to the ground plane.*

Background:
Air is the most common insulation material in the power system. Air at STP (760 mm Hg/ 20 °C) is a good electrical insulating material, but when the local E-field exceeds about 30 kV/cm (3 kV/mm) the air becomes ionised, electrical discharges are initiated that may lead to flashover. In a uniform field, flashover will follow immediately , but in non-uniform fields partial discharges (corona) occur in those regions where the field exceeds the ionisation threshold. Corona is accompanied by audible noise, radiation of bluish and UV light and the formation of ozone (O_3). In the case of the non-uniform field, a further increase in voltage is usually required to allow the discharges to develop into full flashover.

1 DC tests
The test circuit for DC tests is shown schematically in Fig. 1. The circuit is basically a half wave rectifier circuit, charging capacitor C and can generate voltages up to 140 kV.
Note the following features of the circuit.

- An automatic earthing switch is used to discharge the capacitor when the power is switched off.
- The voltage is developed with respect to the ground plane.
- The high voltage is measured, using a resistive voltage divider. R_2

(140 megohm) is the high voltage resistor and R_1, the low voltage resistor is housed inside the voltmeter. Since R_1 <<R_2, the voltage across the voltmeter is of the order of 100 V. The voltmeter is calibrated in terms of the high voltage (in kV).

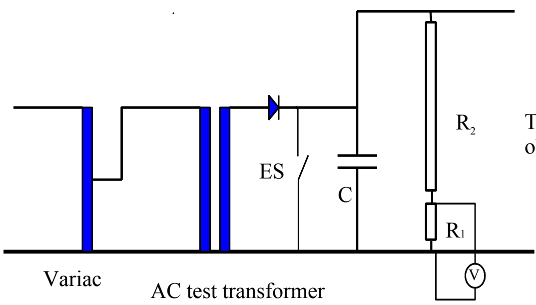


Figure 1: Laboratory set-up for DC tests

Use the different test objects, listed in Table 1, and obtain the flashover voltage by slowly increasing the voltage until flashover. Upon flashover the voltage collapses.

Repeat measurements for the 40 mm point-plane gap but place a perspex shield at the following distances from the tip of the point: 0 mm, 5 mm, 20 mm and 40 mm.

2. AC Tests

The test circuit for the AC tests consists of the variac and high voltage test transformer as shown in Fig. 2. A current limiting resistor is connected in series. In the case of AC the voltage divider can be either capacitive or resistive. The sphere gap is shown as test sample, but is also use ad a rough calibration of measuring circuits, as the flashover of a sphere gap is reasonably accurately predictable. Tables, relating the gap size to flashover voltage as well as

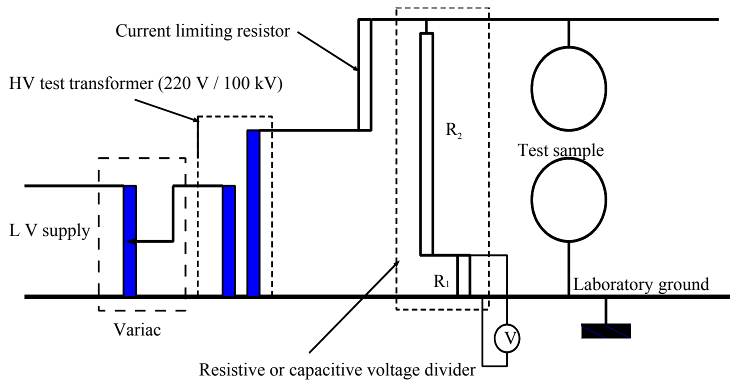


Figure 2: Laboratory set-up for AC testing

air density correction procedures, are given in the Appendix.

Change the circuit in accordance with Fig. 2 and repeat the measurements. Note that the voltmeter measures peak values, but is calibrated in terms $V_{peak}/\sqrt{2}$, i.e. rms if the voltage is sinusoidal.

Table 1: DC and AC Test results:

Description of object	Gap (mm)	Corona onset voltage (kV) peak			Flashover voltage (kV) peak			
		AC*	DC+	DC-	AC*	DC+	DC-	Table (Appendix)
A) 100 mm sphere gap	10				29.7			31.7
	20				55			58
	40				106			106
B) Conically shaped rod / plane gap	10	-	-	-	9.9	15	14	
	20	21.2	18	20	22.6	18	29	
	40	25.5	27	27	31.1	30	55	
C) 50 mm sphere/ plane gap	10				31.1			
	20				48			
	40				69.3			

**NB: The ac voltmeter measures $V_{peak}/\sqrt{2}$.*

Temperature (degrees C):	23	Barometric pressure (mm Hg)	751

Assignment:

a) Compare the measured flashover voltages of the sphere gaps with the values given in the Appendix. Apply air density correction. Whose Law determines this correction?

....
...

p = 751mm Hg
T = 23degr C
d = p*298/(760*(273+T))
d = 0.994835
k = 0.99

From table:							
	kV	kc (corr)	Meas.	%error			
10	31.7	31.383	29.7	-5.36278			
20	58	57.42	55	-4.21456			
40	106	104.94	106	1.010101			

- Agreement within +-6%
- Paschen's Law

b) Why is corona not observed in all cases?

- Corona only occurs in non-uniform fields, at sharp points.
- In the case of small uniform gaps, corona and flashover occurs simultaneously.

c) Explain why different values of flashover voltage are measured for the same electrode spacing with differing types of voltage (DC+, DC- and AC):

- DC+ gives lowest f/o voltage: effect of positive space charge.
- AC flashover at the positive peak. Note the "reasonable" correspondence of DC+ and AC flashover values.

	AC	DC+
10	9.9	15
20	22.6	18
40	31.3	30

d) Calculation: Use the voltages measured at corona inception and flashover to calculate the corresponding value of the maximum field strength for the 50 mm sphere/ plane.

The calculated field strength is of the order of 3.8 to 4 kV/mm, somewhat lower than expected.

Part 2: AC Flashover of Insulators and other Demonstrations

1 The test circuit:

The AC test circuit in the main laboratory is shown in Fig. 1.

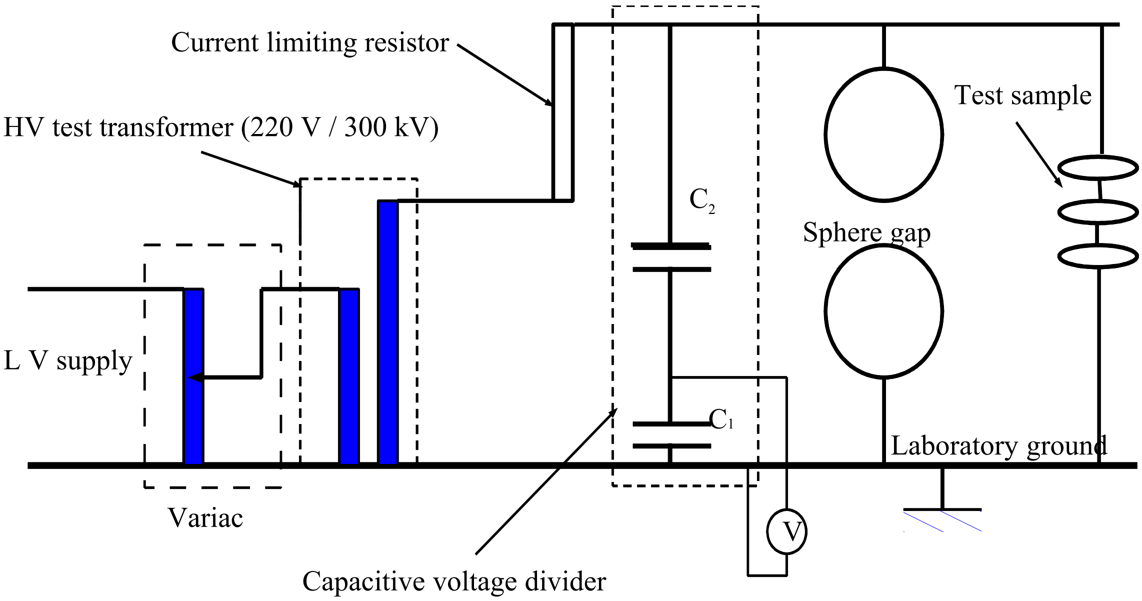


Figure 1: Laboratory set-up for AC testing

a) The flashover of a 4-disc string of insulators.

One disc is usually used on a three phase line, having a line-to-line voltage of 11 kV, i.e. the voltage across one disc is $11/\sqrt{3} = 6.35$ kV. Likewise a rough rule of thumb is that each disc represents 11 kV; a 66 kV line will thus have 6 discs.

Results:

Description	Peak Flashover voltage (kV)/$\sqrt{2}$
1 clean disc	
2 clean discs	
3 clean discs	
2 polluted (wet salt layer) discs and one clean disc.	

Discuss:
- Increase in flashover voltage not quite linear with no of discs.
- The polluted disc is entirely conducting, resulting in the full voltage appearing across the clean discs.
- The clean discs flash over.
- Conducting layer eventually dries out due to the leakage current, flowing in the layer.

b) The effect of the Electric field:

A fluorescent lamp lights up due to the electric field. The field accelerates the electrons and gas molecules inside the tube, thus causing the fluorescent tube to glow due to the electron collisions. The earthed bars provides a screen against the electric field

Discuss:

- The fact that the fluorescent tube lights up is proof that an electric field exists in the vicinity of high voltage conductors.
- The field is sufficient to ionize the gas molecules inside the tube to such an extent that they cause the fluorescent layer to glow.

c) Surface discharge against the wall:

An HV (AC) electrode is insulated from the earthed wall by a glass plate. The air on the surface of the glass breaks down, causing a spectacular surface discharge.

Discuss by referencing relevant sections in the notes:

- See notes

a) Floating object:

An object is insulated from the high voltage line and earth, but is capacitively coupled to the HV, thus attaining such a high voltage that it sparks across to an earthed object.

Discuss by referencing relevant sections in the notes:

- See notes

e**) Corona on "Jacob's Ladder" , developing into an arc**:

One of two horns is connected to earth while the other is connected to HV. As the voltage is raised, corona develops at the sharp points and on thin connecting wires, causing a visual display. As the voltage is raised further, a flashover occurs and a power frequency arc is established between the horns. The arc moves upwards due to the hot ionised gases rising by convection.

Discuss:

- See relevant sections in the notes, dealing with corona and arcs.

HIGH VOLTAGE LABORATORY

PRACTICAL 2: IMPULSE TESTING

SAFETY MEASURES:
• *Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors).* • *A copper sheet serves as the ground reference. This sheet is connected to ground. It is important to ensure good connections to the ground plane.*

Purpose of the experiment:

The purpose of the experiment is to show how the 50 % impulse flashover voltage of several 100 mm air gaps is influenced by the geometry of the electrodes and by the polarity of the impulse voltage.

Background :

The difference between impulse testing and AC and DC tests is that the impulse generator produces a single impulse and not a continuous voltage output.
The outcome of a test is therefore either a flashover or a withstand. The 50% flashover voltage (U_{50}) is the peak value of the impulse that results in 5 flashovers and 5 withstands when 10 impulses are consecutively applied.
A typical impulse wave is shown in Fig.1 and a typical single stage impulse generator to generate such a wave is shown in Fig.2. For the standard lightning impulse: T_1=1,2 µs and T_2=50 µs.

The capacitor C_1 is charged by the HVDC supply. Once the stress across the gap G reaches the flashover conditions, C_1 discharges into the rest of the circuit, resulting in the required waveshape appearing across C_2 and the test object. The component values are chosen to yield

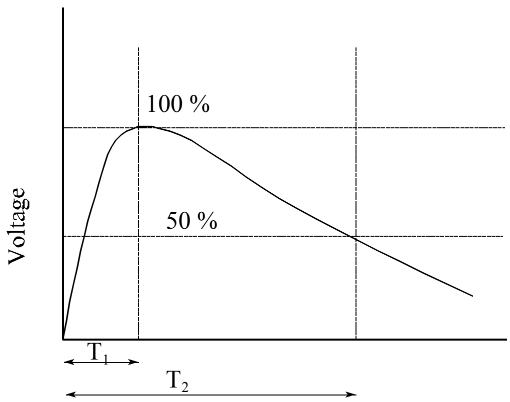


Figure 1: Standard impulse wave

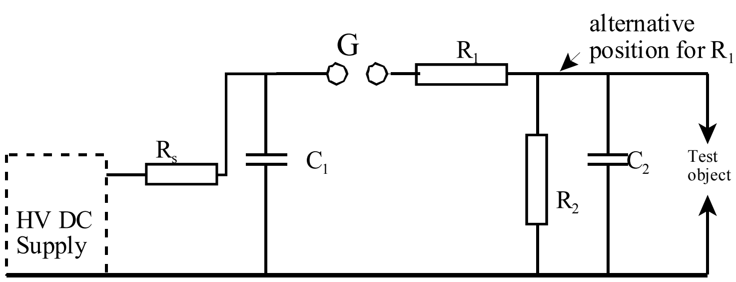


Fig. 2: Single stage impulse generator

the correct wave shape. The gap G can often be triggered externally.

Two-stage impulse generator

- Study the operation of the 2-stage impulse generator shown in Fig. 3. . The capacitors C_S are initially charged in parallel and upon triggering of the gaps they are connected in series and discharge into the rest of the circuit, producing the desired lightning impulse wave across the output capacitors C_B.
- Obtain the 50% flashover voltage for objects, given in Table 1.

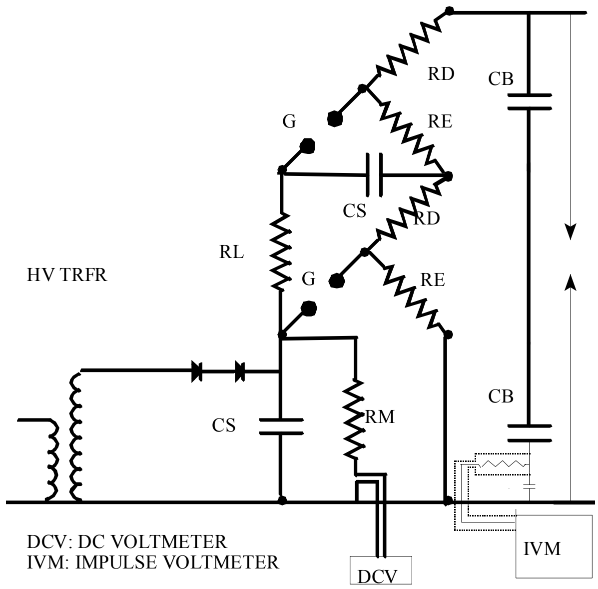


Fig. 3: Two stage impulse generator

Table 1: Results for impulse tests

N.B. Typical AC, DC+ and DC- data values provided for Prac. 1

		Prac. 1			50 % Flashover voltage (kV) peak				
Description of object	Gap (mm)	AC	DC+	DC-	Pos. Impulse		Neg. Impulse		Table (App.)
					DC	Osc.	DC	Osc.	
100 mm sphere gap	40	*106*	*108*	*108*	***60***	***109.6***			*108*
Conically shaped rod / plane gap)	40	*35*	*30*	*55*	***30***	***48.6***	***40***	***76***	

Temperature (degrees C):	19 degr C	Barometric pressure (mm Hg)	744

Discussion:

1. Describe briefly the procedure to obtain the 50% flashover voltage of a test sample:

It is also important to note that flashover is a statistical phenomenon as it depends on the availability of initialising electrons and other environmental influences. Even with AC and DC tests, a certain statistical variation is to be expected. With impulse testing, the critical flashover value as shown in Fig. 4.17 is not well-

defined. In consecutive tests near this value on the same gap, some tests will result in flashover and others in withstand. The critical flashover voltage (CFO) is therefore defined as the 50 % flashover voltage. Out of 10 tests, an impulse with a peak value equal to the CFO will result in 5 flashovers and 5 withstands. This can also be seen from Fig. 4.18 where the flashover probability is shown as a function of impulse voltage.

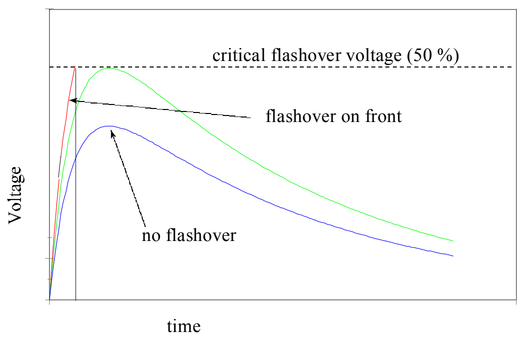


Fig. 4.17: Impulse flashover – time to flashover

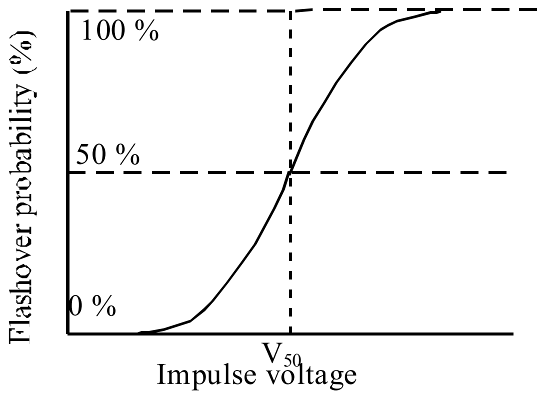


Fig. 4.18: Impulse flashover probability.

2 How is the impulse generator adjusted to obtain a ***higher*** impulse?

By adjusting the gaps (G) on the impulse generator. Increasing the DC charging voltage does not affect the peak, but just the frequency of the charge/ discharge cycles.

3 Compare the impulse flashover voltages with AC and DC flashover. Why are the values different?

The impulse flashover voltage is higher since the energy content in a single impulse is limited. In DC and AC testing the source supplies energy to the discharges that develop into an arc until switched off.

4 Compare the positive and negative impulse flashover values. Why are the values different?

The same answer as for Prac 1(AC & DC): The positive space charge distort the field in the gap in such a way as to aid flashover in the positive case and to suppress flashover in the negative case.

5 Compare the measured values for the sphere gap with those obtained from the corrected tables in the Appendix of Prac 1:

d=p*298/(760*(273+T))= 744*298/(760*(273+19)) = 0.999
The compensated value is therefore: 0.999*108=107.9 kV, compared to the measured 109.6 kV.
% error=(109.6-107.9)*100/107.9= 1.6 %

Eight stage impulse generator

The operation of the 8-stage, 1,4 MV, 1600 kJ impulse generator, shown in Fig. 4, is similar to that of the two-stage model. The triggering unit of the 8-stage generator is not operational and the generator is used in the free running mode.
The following demonstrations will be done with the 8-stage impulse generator:

1 The positive impulse flashover of a 66 kV insulator string.
2 The principles of lightning protection of a house.

Discussion:

a) Compare the impulse flashover voltage of the insulator string with the power frequency flashover voltage (aprox. 6*70 = 420 kV (rms))

....

.............Measured :50% FOV = 525 kV (again higher see Q. 3 in first part)

2 What are the main principles of lightning protection

- Proper lightning protection with adequate protection angle to intercept the lightning leader and to conduct the lightning current to ground, without having to flow through the structure of the building.
- Mast to have a low earthing impedance to minimise touch and step potentials.

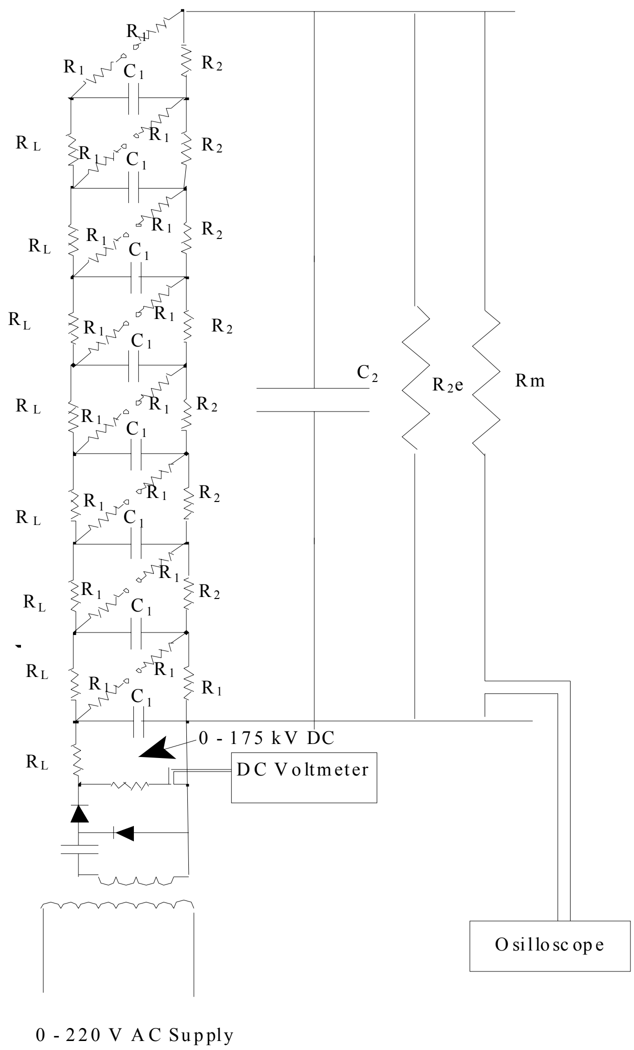


Figure 4: 8- stage impulse generator

Appendix

Table 7.3 Peak value of sparkover voltage in kV for a.c., d.c. voltages of either polarity, and for full negative standard impulse voltages (one sphere earthed) (a) and positive polarity impulse voltages and impulse voltages with long tails (b) at temperature: 25°C and pressure: 760 torr

Gap spacing (cm)	Sphere diameter (cm)															
	5		10		15		25		50		100		150		200	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.5	17.4	17.4	16.9	16.8	16.9	16.9										
1.0	32.0	32.0	31.7	31.7	31.4	31.4	31.2	31.4								
1.5	44.7	45.5	44.7	45.1	44.7	45.1	44.7	44.7								
2.0	57.5	58.0	58.0	58.0	58.0	58.0	58.0	58.0								
2.5			71.5	71.5	71.5	71.5	71.5	71.5	71.5	71.5						
3.0			85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0						
3.5			95.5	96.0	97.0	97.0	97.0	97.0	97.0	97.0						
4.0			106.0	108.0	108.0	110.0	110.0	110.0	110.0	110.0						
5.0			(123.0)	(127.0)	127.0	132.0	135.0	136.0	136.0	136.0						
7.5					(181.0)	(187.0)	195.0	196.0	199.0	199.0						
10.0							257	268	259	259	262	262	262	262	262	262
12.5							277	294	315	317						
15.0							(309)	(331)	367	374	383	384	384	384	384	384
17.5							(336)	(362)	413	425						
20.0									452	472	500	500	500	500	500	500
25.0									520	545	605	610				
30.0									(575)	(610)	700	715	730	735	735	740
35.0									(725)	(755)	785	800				
40.0											862	885	940	950	960	965
45.0											925	965				
50.0											1000	1020	1110	1130	1160	1170
75.0											(1210)	(1260)	1420	1460	1510	1590
100.0															1870	1900

$$V = kV_0$$

where k is a function of the air density factor d, given by

$$d = \frac{p}{760}\left(\frac{293}{273+T}\right) \qquad (7.22)$$

The relationship between d and k is given in Table 7.6.

Table 7.6 Relation between Correction Factor k and Air Density Factor d

d	0.70	0.75	0.80	0.85	0.90	0.95	1.0	1.05	1.10	1.15
k	0.72	0.77	0.82	0.86	0.91	0.95	1.0	1.05	1.09	1.12

about the book . . .

This book is a basic ***student's guide*** to the practice and theory of ***high voltage engineering***. Electrical engineers, utility staff and consultants will also greatly benefit.

The book includes the following topics: High Voltage Power Systems, Electrostatic Fields, Gas discharges, Solid and Liquid Insulating Materials, Composite Insulation Systems, High Voltage Laboratory Tests, Power System Overvoltages and Insulation Coordination, and Electrical Safety when dealing with High Voltage.

The theory is presented in an easy to understand manner using practical worked out examples and laboratory experiments. IEC standards and SI units are used throughout.

Everything a student needs to know about the basic practice and theory of high voltage engineering . . .

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